

Neutrino Seminar Series



Photon Emission in NC interactions with nucleons and nuclei

L. Alvarez-Ruso, J. Nieves, E. Wang

IFIC, Valencia

Introduction

■ Photon emission in NC interactions:

■ on nucleons $\nu(\bar{\nu}) N \rightarrow \nu(\bar{\nu}) \gamma N$

■ on nuclei $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$ ← incoherent

$\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$ ← coherent

$\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) A'^* N'$

Ankowski et al., PRL 108 (2012), 052505



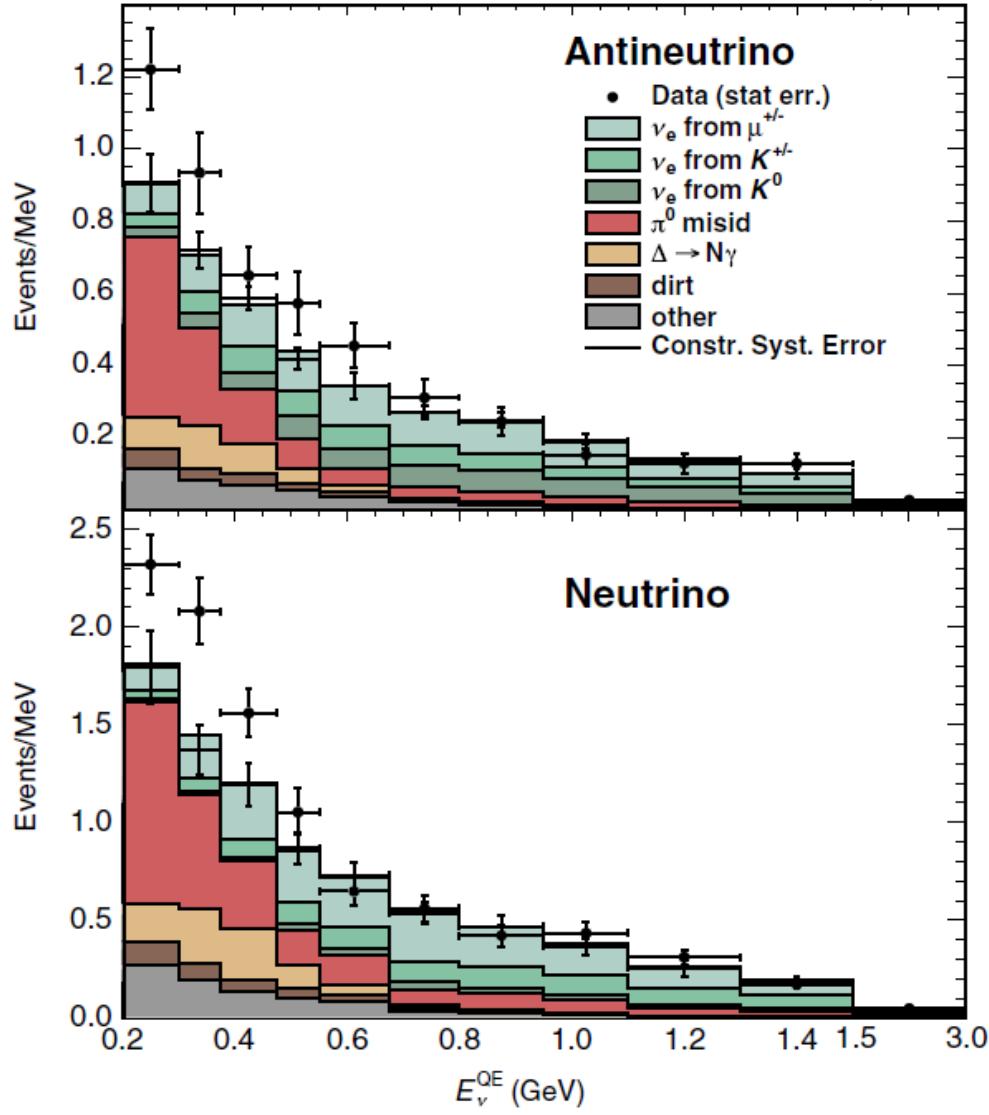
■ Small cross section (weak & e.m.)

but

■ Important background for $\nu_\mu \rightarrow \nu_e$ studies (θ_{13} , δ) if γ is misidentified as e^\pm from CCQE $\nu_e n \rightarrow e^- p$ or $\bar{\nu}_e p \rightarrow e^+ n$

Introduction

- e-like events in the MiniBooNE $\nu_\mu \rightarrow \nu_e / \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search:

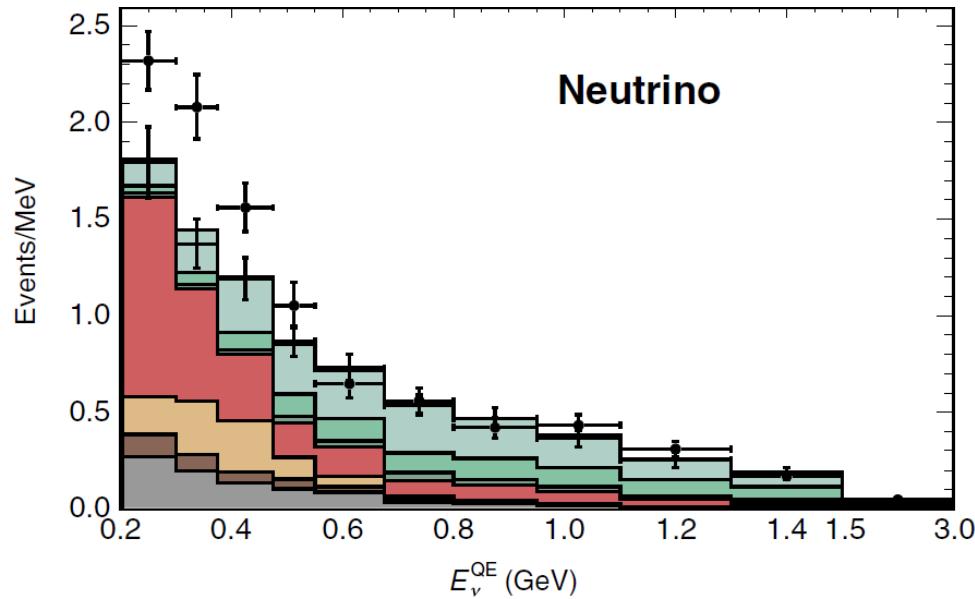


reconstructed ν energy

$$E_\nu^{\text{QE}} = \frac{2m_n E_e - m_e^2 - m_n^2 + m_p^2}{2(m_n - E_e + p_e \cos \theta_e)}$$

Introduction

- e-like events in the MiniBooNE $\nu_\mu \rightarrow \nu_e$ search:

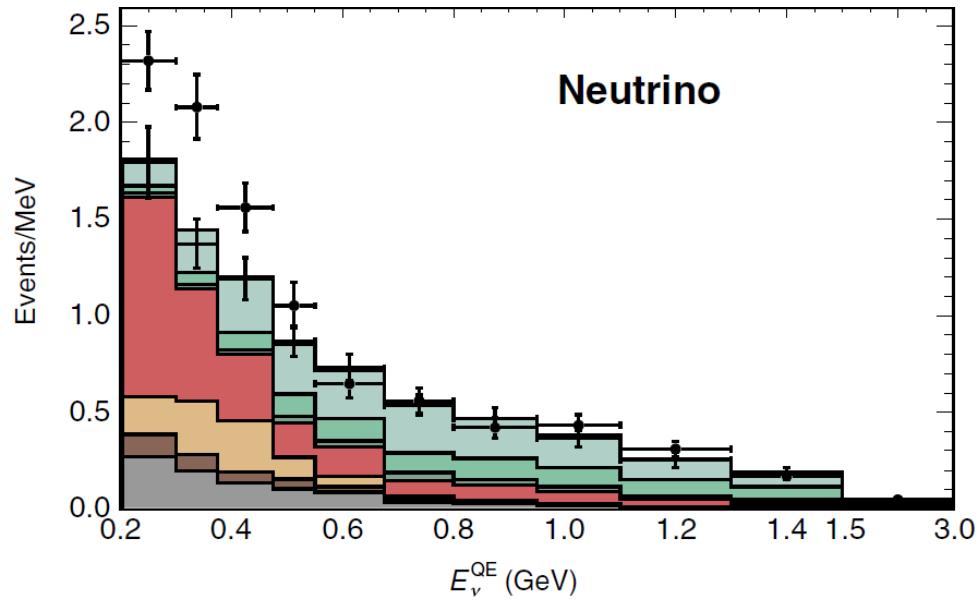


Aguilar-Arevalo et al., PRL110 (2013) 161801

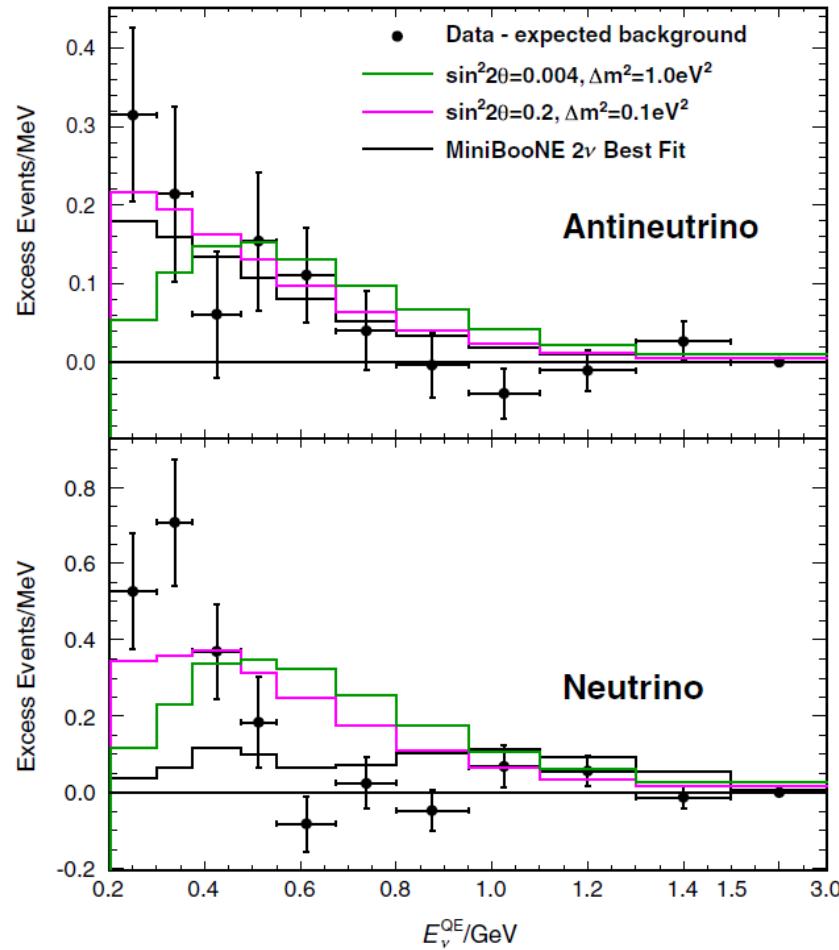
- Unexplained excess of events at $200 < E_\nu^{QE} < 475$ MeV

Introduction

- e-like events in the MiniBooNE $\nu_\mu \rightarrow \nu_e$ search:



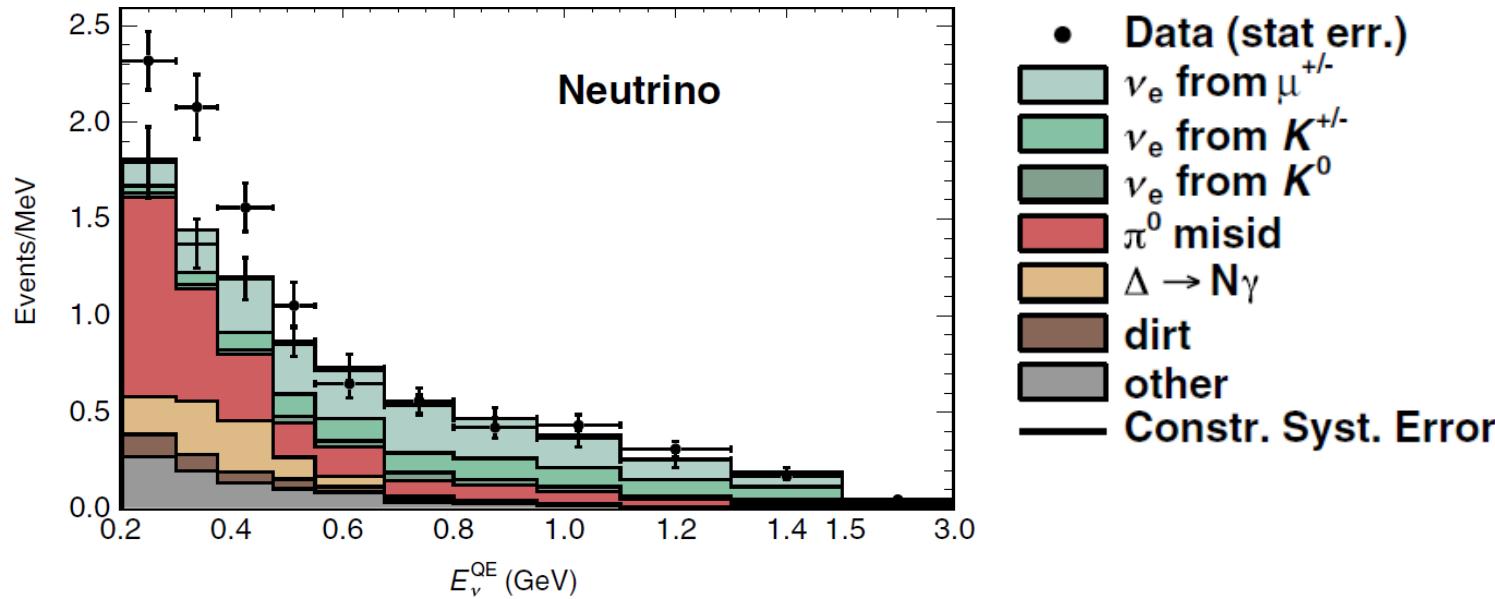
Aguilar-Arevalo et al., PRL110 (2013) 161801



- Only marginally compatible with a two-neutrino oscillation model
- Small overlap with LSND

Introduction

- e-like events in the MiniBooNE $\nu_\mu \rightarrow \nu_e$ search:

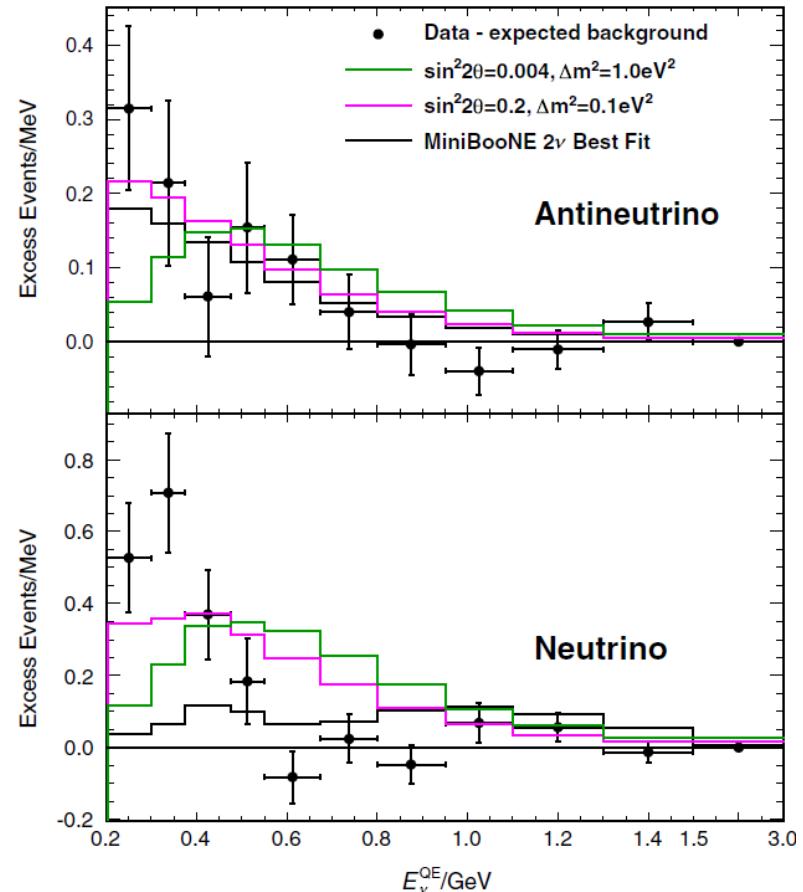
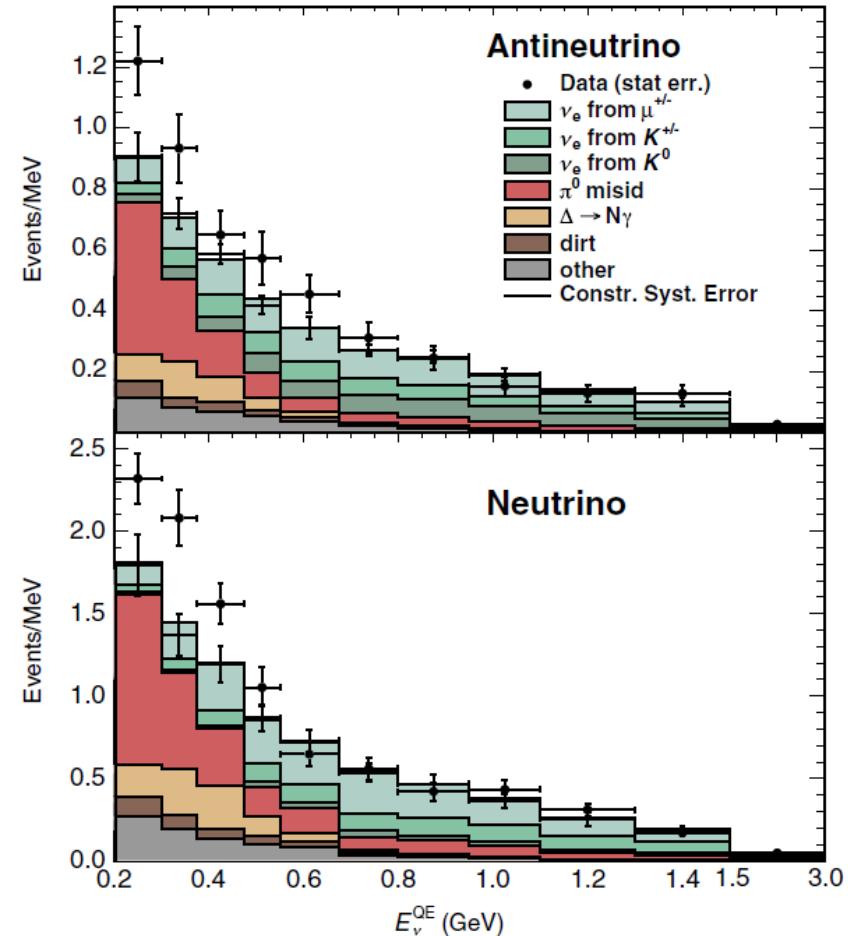


Aguilar-Arevalo et al., PRL110 (2013) 161801

- Unexplained excess of events at $200 < E_\nu^{\text{QE}} < 475$ MeV
 - NC π^0 production ← largest background
 - NC $\Delta \rightarrow N\gamma$ ← 2nd largest background: determined from the number of measured NC π^0 events

Introduction

- e-like events in the MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search:

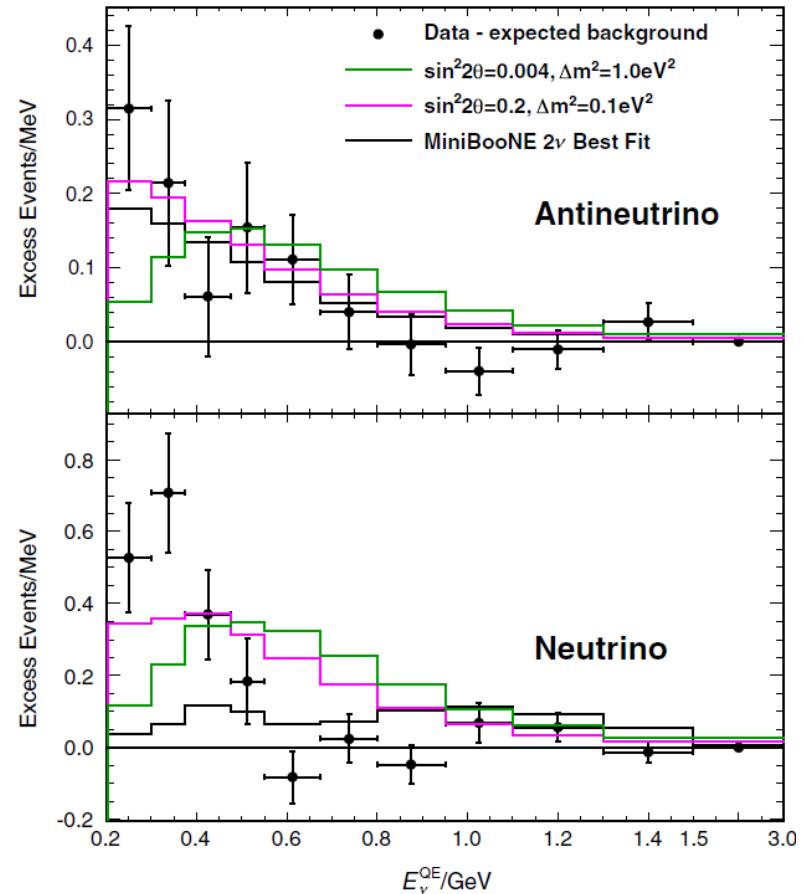
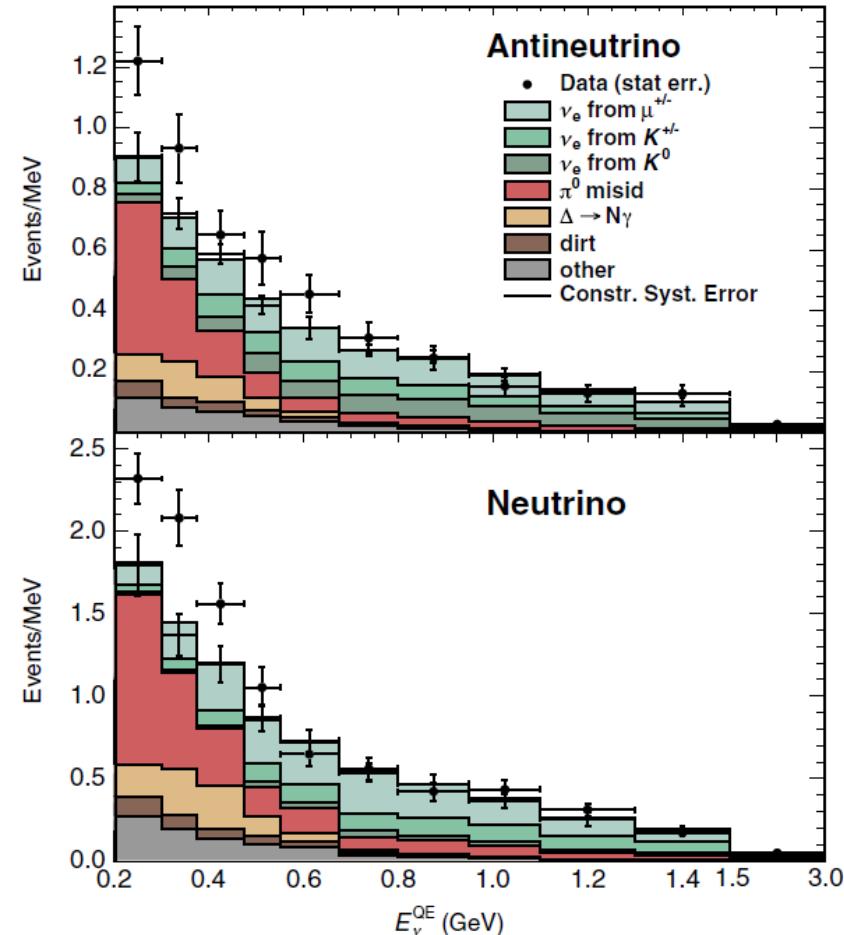


- Oscillation hypothesis more probable
- Consistent in part with LSND and with the KARMEN limits

Aguilar-Arevalo et al., PRL110 (2013) 161801

Introduction

- e-like events in the MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search:



- At $200 < E_\nu^{\text{QE}} < 475 \text{ MeV}$
 - NC π^0 production ← largest background
 - NC $\Delta \rightarrow N\gamma$ ← 3^d largest background

Aguilar-Arevalo et al., PRL110 (2013) 161801

Introduction

- e-like backgrounds @ MiniBooNE are constrained **in situ**...

Introduction

- e-like backgrounds @ MiniBooNE are constrained **in situ**...
... but some are more constrained than others.
 - NC π^0
 - measured @ MiniBooNE
 - Rein-Sehgal **resonance** production model + non-resonant background
 - π FSI
 - NC $\Delta \rightarrow N \gamma$
 - relies on the determination of weak N-R vertices
 - No background
 - No coherent channel

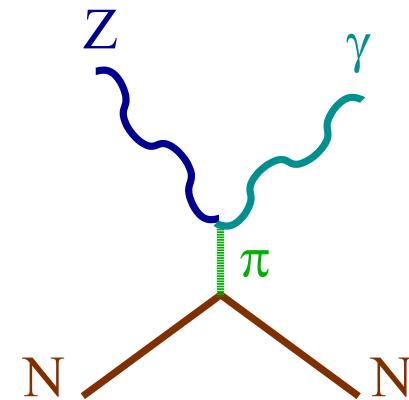
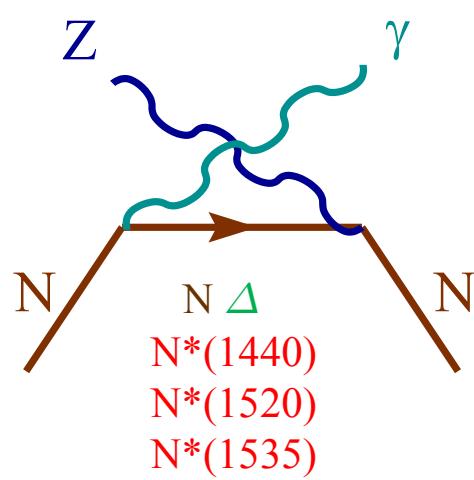
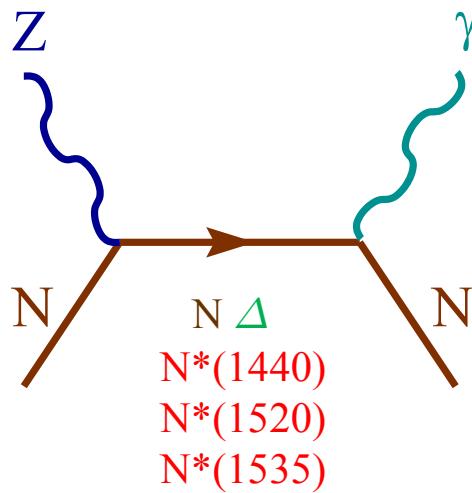
Introduction

- Models:
 - R. Hill, PRD 81 (2010); 84 (2011)
 - Hadronic degrees of freedom N , $\Delta(1232)$, π , ρ , ω
 - EFT θ consistent with the SM symmetries at low energy
 - Extrapolation to $E_\nu \sim 1\text{-}2$ GeV using phenomenological form factors
 - Applied to MiniBooNE e-like events but without nuclear corrections

- Zhang & Serot, PRC 86 (2012) 015501, 035502, 035504
- EFT θ on nucleons
- Includes N , $\Delta(1232)$, π but also higher orders/heavy meson fields at tree level (no loops)
- Applied to incoherent and coherent reactions on nuclei
- Extended to higher energies using form factors to study MiniBooNE excess of events, PLB 719 (2013)

The model

Feynman diagrams:



The model

■ Amplitude:

$$\mathcal{M}_r = \frac{G_F e}{\sqrt{2}} \epsilon_\mu^{*(r)} \bar{u}(p') \Gamma^{\mu\alpha} u(p) l_\alpha$$

G_F ← Fermi constant

e ← electric charge

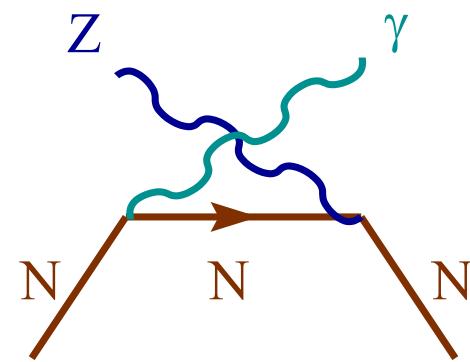
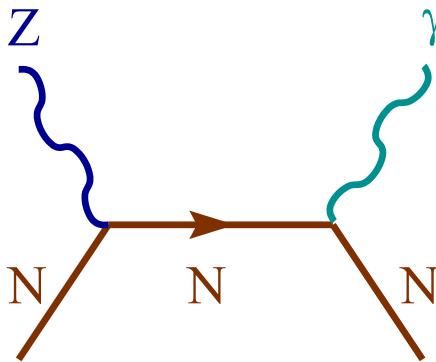
$\epsilon_\mu^{*(r)}$ ← photon polarization

l_α ← NC for ν or $\bar{\nu}$

$\Gamma^{\mu\alpha}$ ← specific for each mechanism

The model

Nucleon pole terms:



$$\Gamma^{\mu\alpha} = J_{\text{EM}}^\mu(-q_\gamma) D_N(p+q) J_{\text{NC}}^\alpha(q) + J_{\text{NC}}^\alpha(q) D_N(q_\gamma - p) J_{\text{EM}}^\mu(-q_\gamma)$$

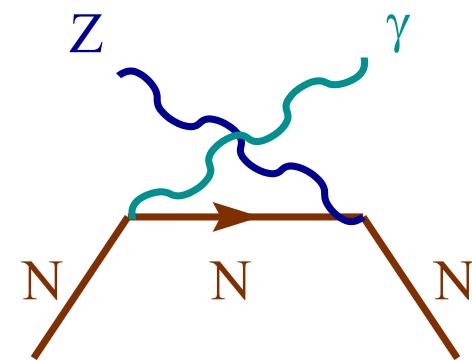
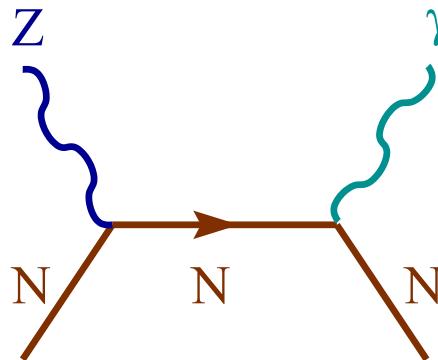
$q \leftarrow$ 4-momentum transferred to the nucleon

$q_\gamma \leftarrow$ photon 4-momentum

$$D_N(p) = \frac{1}{\not{p} - m_N} \leftarrow \text{nucleon propagator}$$

The model

■ Nucleon pole terms:



$$\Gamma^{\mu\alpha} = J_{\text{EM}}^\mu(-q_\gamma) D_N(p+q) J_{\text{NC}}^\alpha(q) + J_{\text{NC}}^\alpha(q) D_N(q_\gamma - p) J_{\text{EM}}^\mu(-q_\gamma)$$

$$J_{\text{NC}}^\alpha(q) = \gamma^\alpha \tilde{F}_1(q^2) + \frac{i}{2M} \sigma^{\alpha\beta} q_\beta \tilde{F}_2(q^2) - \gamma^\mu \gamma_5 \tilde{F}_A(q^2)$$

■ Vector NC form factors:

$$2\tilde{F}_{1,2}^{(p)} = (1 - 4 \sin^2 \theta_W) F_{1,2}^{(p)} - F_{1,2}^{(n)} - F_{1,2}^{(s)}$$

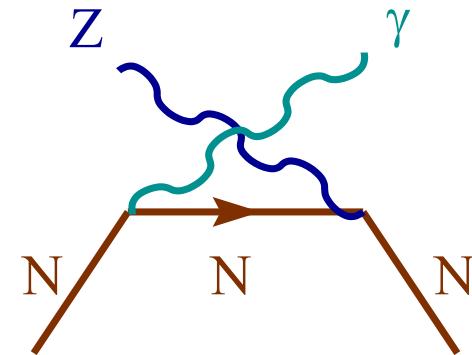
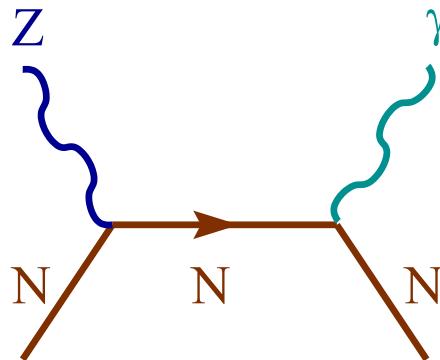
$$2\tilde{F}_{1,2}^{(n)} = (1 - 4 \sin^2 \theta_W) F_{1,2}^{(n)} - F_{1,2}^{(p)} - F_{1,2}^{(s)}$$

■ $F_{1,2}^{(p,n)} \leftarrow$ p,n EM form factors (dipole parametrizations)

■ $F_{1,2}^{(s)} \leftarrow$ strange EM form factors $\rightarrow 0$

The model

■ Nucleon pole terms:



$$\Gamma^{\mu\alpha} = J_{\text{EM}}^\mu(-q_\gamma) D_N(p+q) J_{\text{NC}}^\alpha(q) + J_{\text{NC}}^\alpha(q) D_N(q_\gamma - p) J_{\text{EM}}^\mu(-q_\gamma)$$

$$J_{\text{NC}}^\alpha(q) = \gamma^\alpha \tilde{F}_1(q^2) + \frac{i}{2M} \sigma^{\alpha\beta} q_\beta \tilde{F}_2(q^2) - \gamma^\mu \gamma_5 \tilde{F}_A(q^2)$$

■ Axial NC form factor:

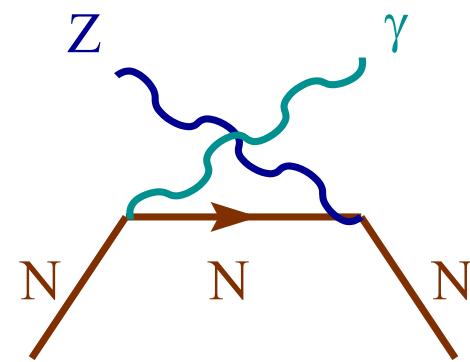
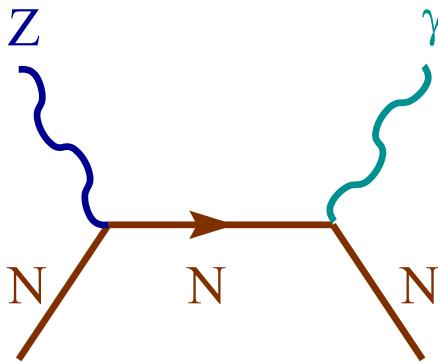
$$2\tilde{F}_A^{(p,n)} = \pm F_A + F_A^{(s)} \quad F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2} \right)^{-2}$$

■ $g_A = 1.267$, $M_A = 1.016$ GeV

■ $F_A^{(s)}$ ← strange axial form factors → 0

The model

Nucleon pole terms:



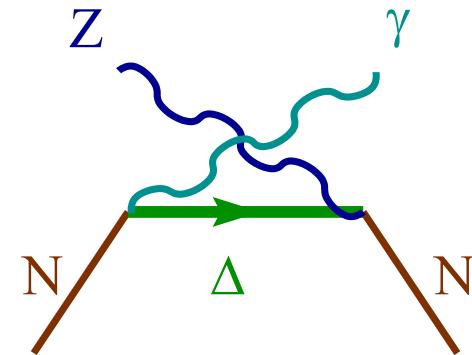
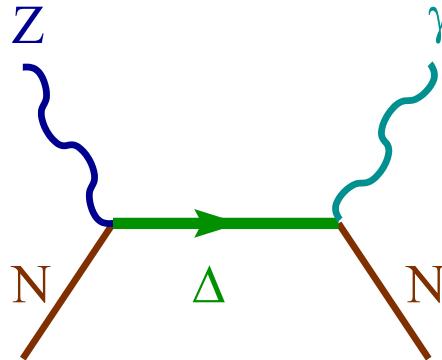
$$\Gamma^{\mu\alpha} = J_{\text{EM}}^\mu(-q_\gamma) D_N(p+q) J_{\text{NC}}^\alpha(q) + J_{\text{NC}}^\alpha(q) D_N(q_\gamma - p) J_{\text{EM}}^\mu(-q_\gamma)$$

$$J_{\text{NC}}^\alpha(q) = \gamma^\alpha \tilde{F}_1(q^2) + \frac{i}{2M} \sigma^{\alpha\beta} q_\beta \tilde{F}_2(q^2) - \gamma^\mu \gamma_5 \tilde{F}_A(q^2)$$

$$J_{\text{EM}}^\mu(-q_\gamma) = \gamma^\mu F_1^{(i)}(0) - \frac{i}{2M} \sigma^{\mu\nu} q_\gamma{}^\nu F_2^{(i)}(0) \quad i = \text{p,n}$$

The model

- $\Delta(1232)$ pole terms:



$$\Gamma^{\mu\alpha} = \hat{J}_{\text{EM}}^{\delta\mu}(p', q_\gamma) D_{\delta\sigma}^\Delta(p + q) J_{\text{NC}}^{\sigma\alpha}(p, q) + \hat{J}_{\text{NC}}^{\delta\alpha}(p', -q) D_{\delta\sigma}^\Delta(q_\gamma - p) J_{\text{EM}}^{\sigma\mu}(p', -q_\gamma)$$

$$\hat{J}^{\alpha\beta} = \gamma_0 (J^{\alpha\beta})^\dagger \gamma_0$$

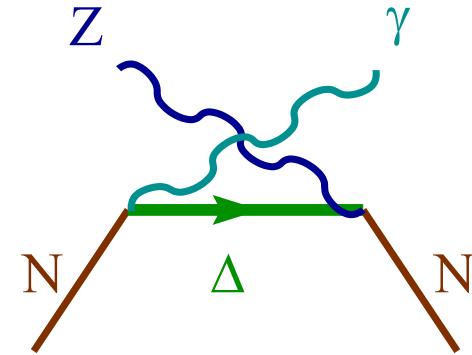
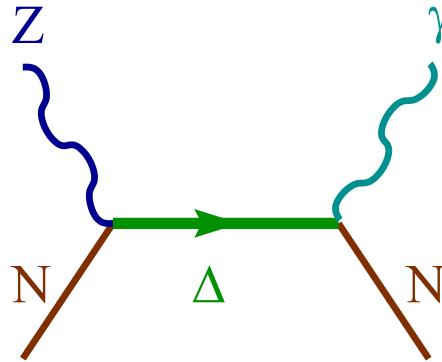
$$D_{\delta\sigma}^\Delta(p) = \frac{\Lambda_{\delta\sigma}}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta(p^2)} \quad \leftarrow \text{Delta propagator}$$

$$\Lambda_{\delta\sigma} \quad \leftarrow \text{N-}\Delta \text{ projector}$$

$$\Gamma_\Delta(p^2) \quad \leftarrow \text{E-dependent width}$$

The model

- $\Delta(1232)$ pole terms:



$$\Gamma^{\mu\alpha} = \hat{J}_{\text{EM}}^{\delta\mu}(p', q_\gamma) D_{\delta\sigma}^\Delta(p + q) J_{\text{NC}}^{\sigma\alpha}(p, q) + \hat{J}_{\text{NC}}^{\delta\alpha}(p', -q) D_{\delta\sigma}^\Delta(q_\gamma - p) J_{\text{EM}}^{\sigma\mu}(p', -q_\gamma)$$

$$J_{\text{NC}}^{\beta\mu}(p, q) = \left[\frac{\tilde{C}_3^V(q^2)}{M} (g^{\beta\mu} q^\mu - q^\beta \gamma^\mu) + \frac{\tilde{C}_4^V(q^2)}{M^2} (g^{\beta\mu} q \cdot p_\Delta - q^\beta p_\Delta^\mu) + \frac{\tilde{C}_5^V(q^2)}{M^2} (g^{\beta\mu} q \cdot p - q^\beta p^\mu) \right] \gamma_5 \\ + \frac{\tilde{C}_3^A(q^2)}{M} (g^{\beta\mu} q^\mu - q^\beta \gamma^\mu) + \frac{\tilde{C}_4^A(q^2)}{M^2} (g^{\beta\mu} q \cdot p_\Delta - q^\beta p_\Delta^\mu) + \tilde{C}_5^A(q^2) g^{\beta\mu}$$

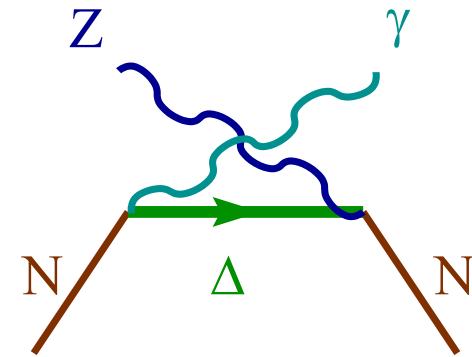
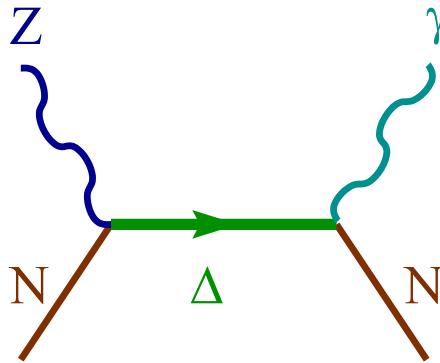
$$J_{\text{EM}}^{\beta\mu}(p, q_\gamma) = \left[\frac{C_3^{(p,n)}(0)}{M} (g^{\beta\mu} q_\gamma^\mu - q_\gamma^\beta \gamma^\mu) + \frac{C_4^{(p,n)}(0)}{M^2} (g^{\beta\mu} q_\gamma \cdot p_\Delta - q_\gamma^\beta p_\Delta^\mu) + \frac{C_5^{(p,n)}(0)}{M^2} (g^{\beta\mu} q_\gamma \cdot p - q_\gamma^\beta p^\mu) \right] \gamma_5$$

$$\tilde{C}_i^V = -(1 - 2 \sin^2 \theta_W) C_i^V \quad C_i^{(p,n)} = -C_i^V$$

$$\tilde{C}_i^A = -C_i^A$$

The model

- $\Delta(1232)$ pole terms:



- $N\text{-}\Delta$ Vector form factors C_i^V can be obtained from helicity amplitudes extracted from π photo- and electro-production

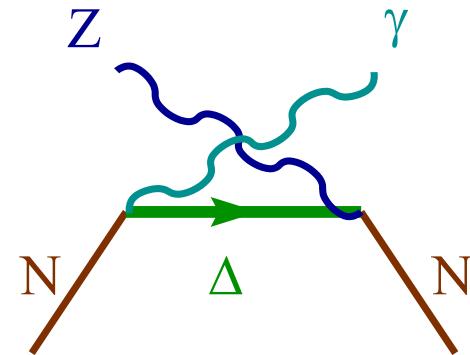
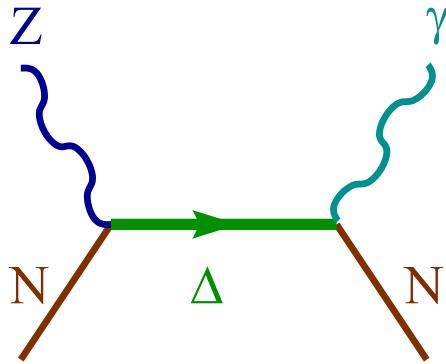
$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \langle R, J_z = 1/2 | \epsilon_\mu^+ J_{\text{EM}}^\mu | N, J_z = -1/2 \rangle \zeta$$

$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \langle R, J_z = 3/2 | \epsilon_\mu^+ J_{\text{EM}}^\mu | N, J_z = 1/2 \rangle \zeta$$

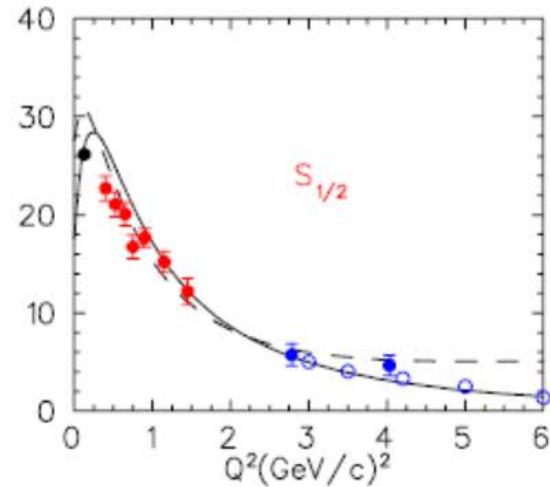
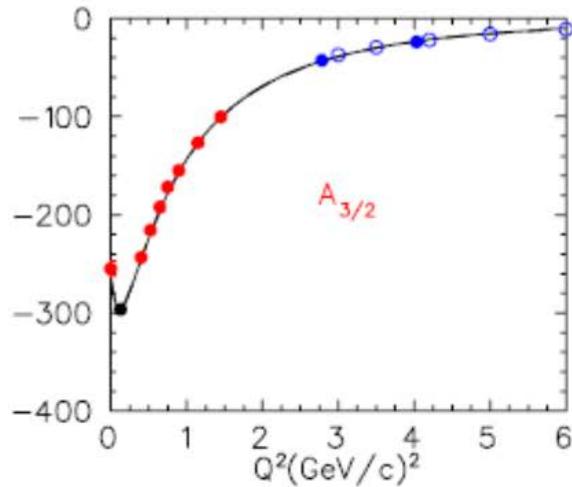
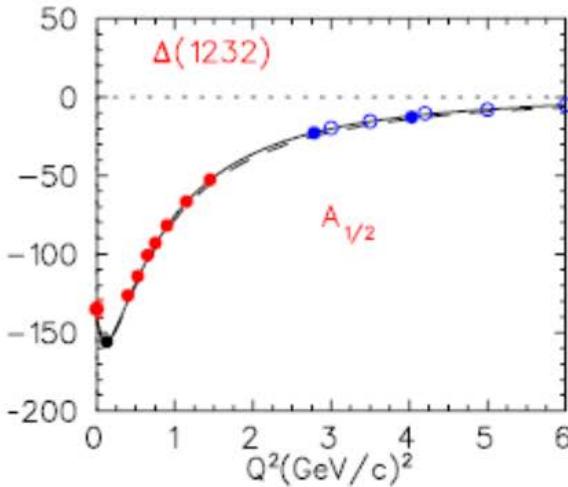
$$S_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}} \frac{|\mathbf{q}|}{\sqrt{Q^2}} \langle R, J_z = 1/2 | \epsilon_\mu^0 J_{\text{EM}}^\mu | N, J_z = 1/2 \rangle \zeta$$

The model

- $\Delta(1232)$ pole terms:



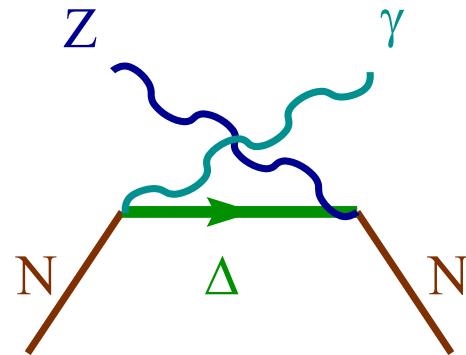
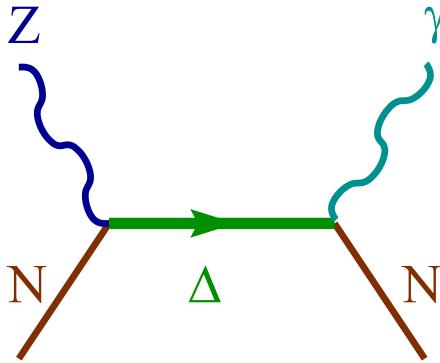
- $N-\Delta$ Vector form factors C_i^V can be obtained from helicity amplitudes extracted from π photo- and electro-production



MAID, Tiator et al., EPJ Special Topics 198 (2011)

The model

- $\Delta(1232)$ pole terms:



- N- Δ Axial form factors C_i^A

$$C_4^A = -\frac{1}{4}C_5^A \quad C_3^A = 0 \leftarrow \text{Adler model}$$

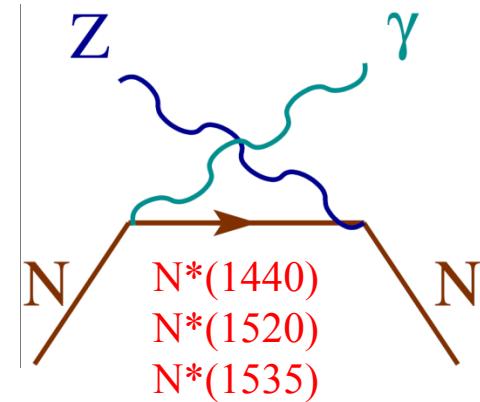
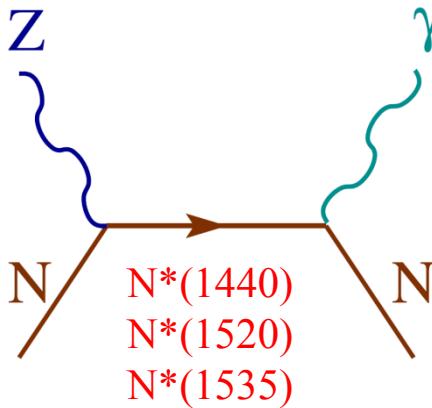
$$C_5^A = C_5^A(0) \left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$

- $C_5^A(0) = 1.00 \pm 0.11$, $M_{A\Delta} = 0.93 \pm 0.07$ GeV

Hernandez et al., PRD 81 (2010)

The model

- N^* pole terms:



- $N-N^*$ Vector form factors can be obtained from helicity amplitudes

- $N-N^*$ Axial form factors:

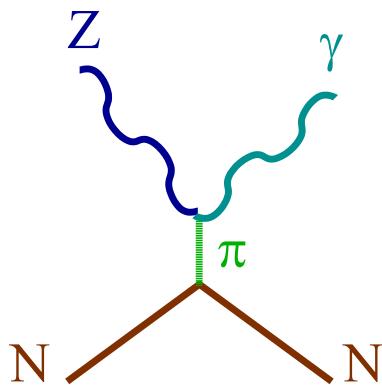
- PCAC $q^\alpha A_\alpha \approx 0$
- π -pole dominance of the pseudoscalar form factor: F_P , C_6^A
- Dipole q^2 dependence

$$F_A, C_5^A(q^2) = F_A, C_5^A(0) \left(1 - \frac{q^2}{M_A^2}\right)^{-2}$$

$$M_A = 1 \text{ GeV}$$

The model

- π pole term:



- from the **anomalous** part of the Lagrangian

$$\Gamma^{\mu\alpha} = -ic_{p,n} \frac{g_A m_N}{4\pi^2 f_\pi^2} \left(\frac{1}{2} - 2 \sin^2 \theta_W \right) \epsilon^{\sigma\delta\mu\alpha} q_\gamma^\sigma q_\delta^\gamma \gamma_5 D_\pi(p' - p) F_\pi(p' - p)$$

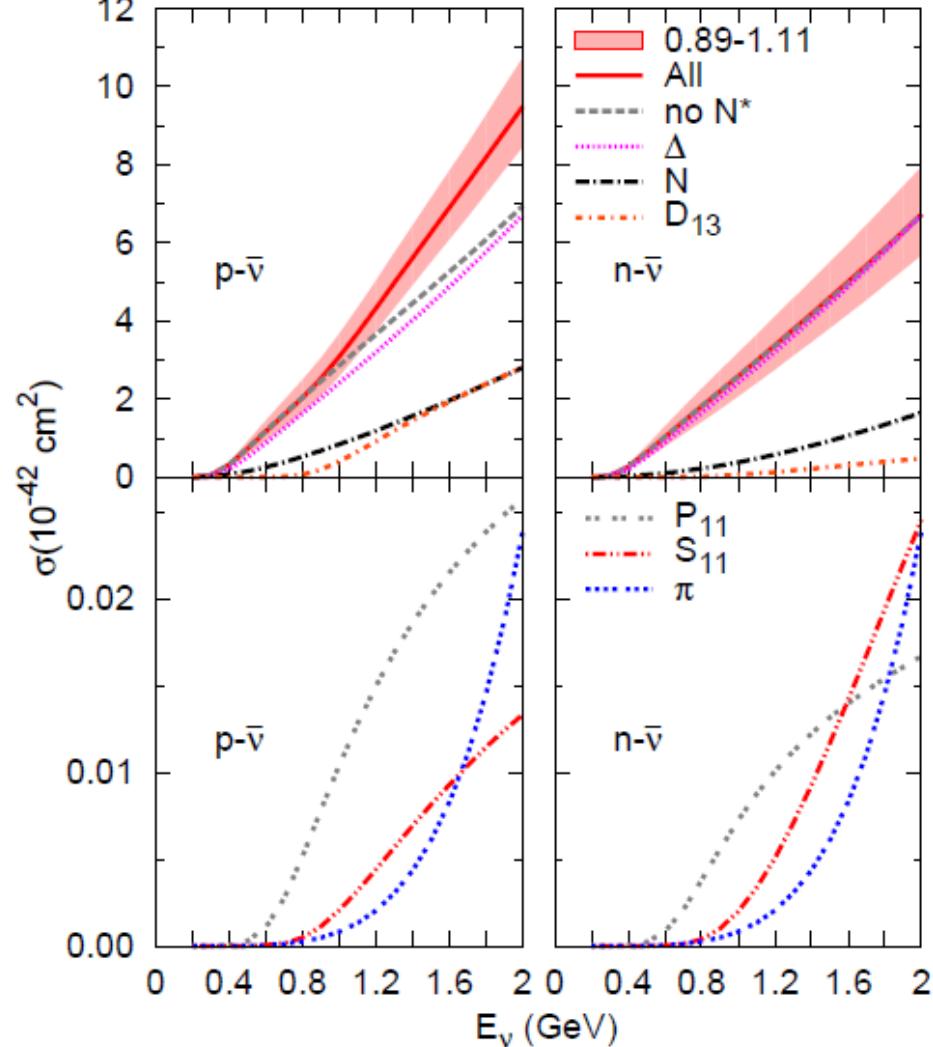
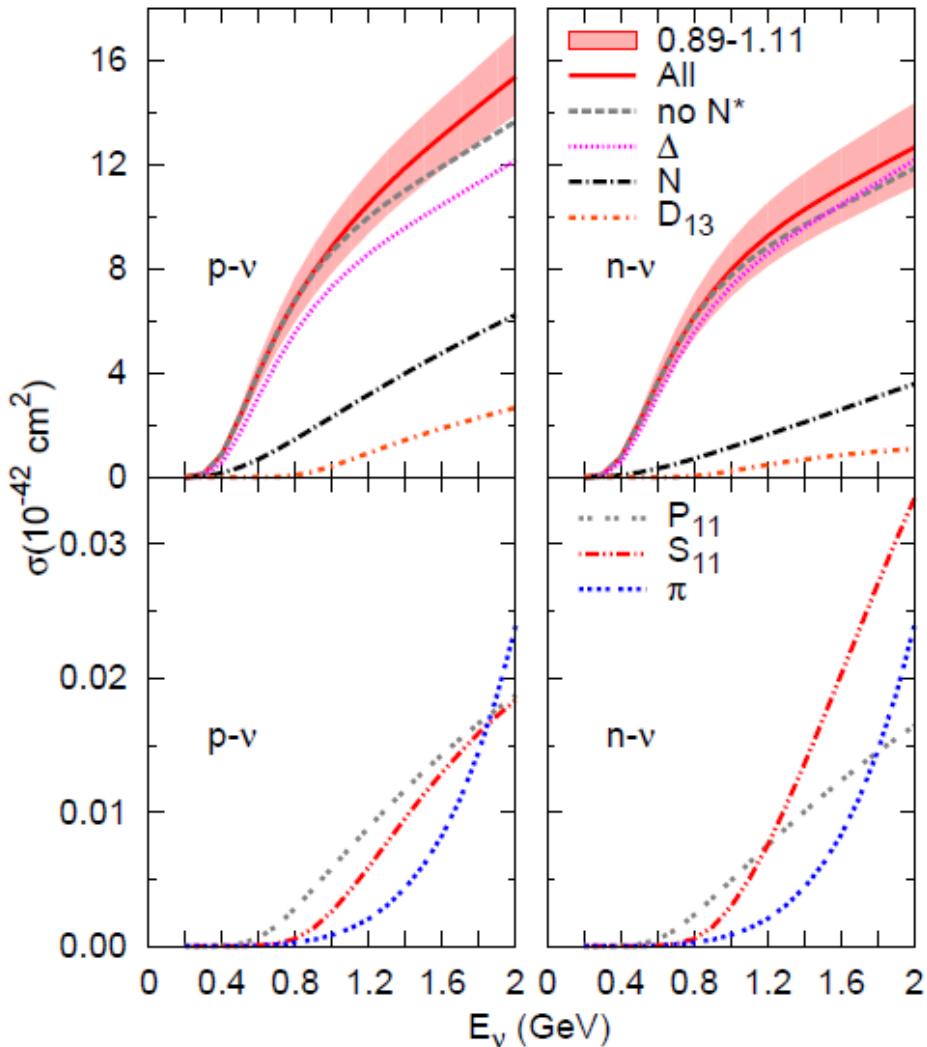
$$D_\pi(p) = \frac{1}{p^2 - m_\pi^2} \quad \leftarrow \pi \text{ propagator}$$

$$F_\pi(p) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - p^2} \quad \Lambda = 1.2 \text{ GeV} \quad \leftarrow \text{off-shell form factor}$$

$$c_{p,n} = \pm 1$$

Results on nucleons

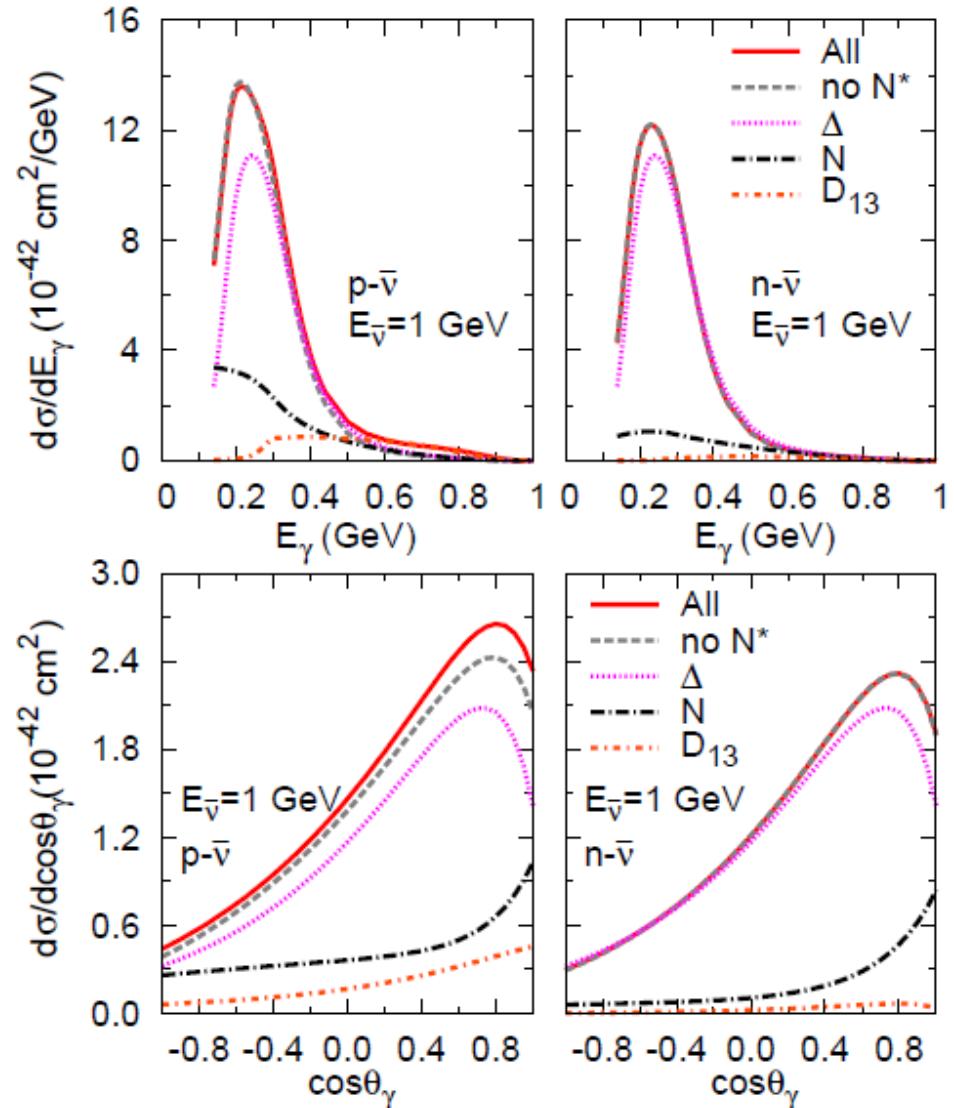
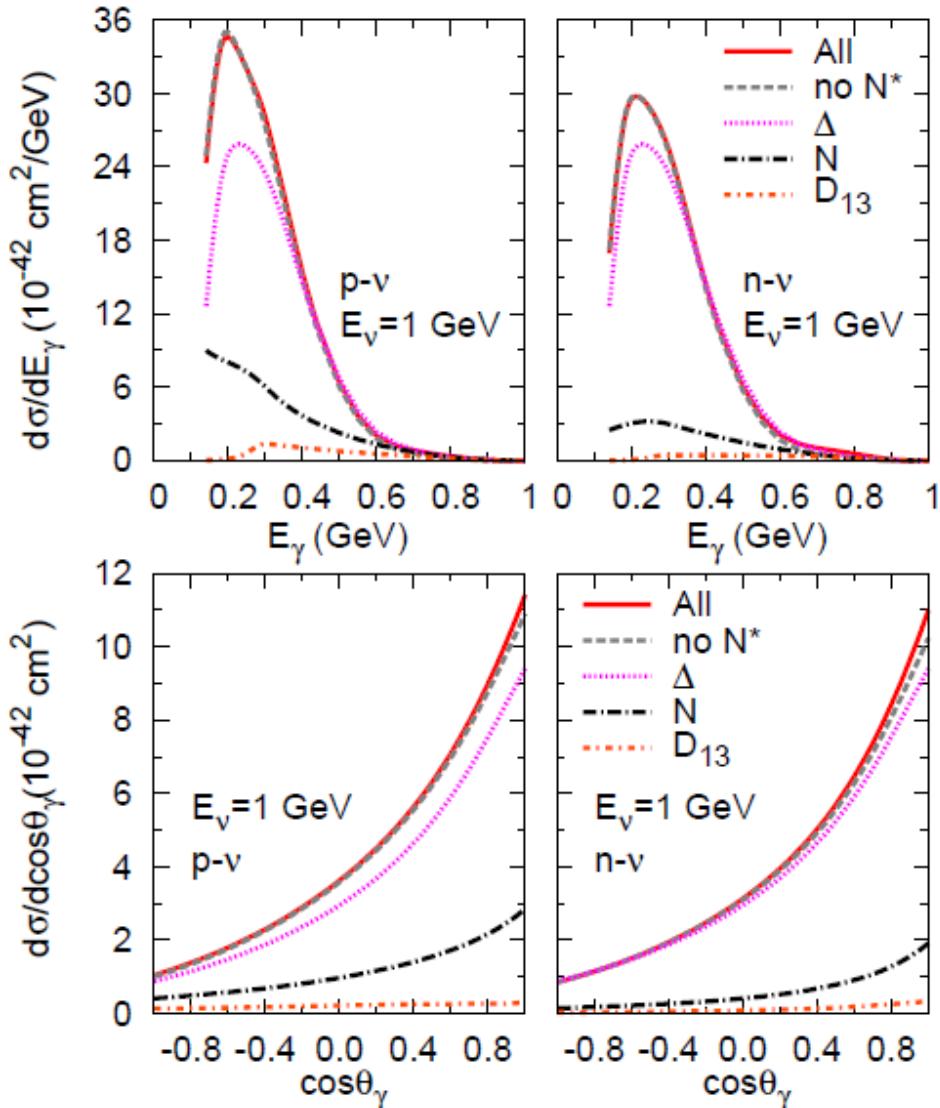
■ Integrated cross sections ($E_\nu > 140$ MeV)



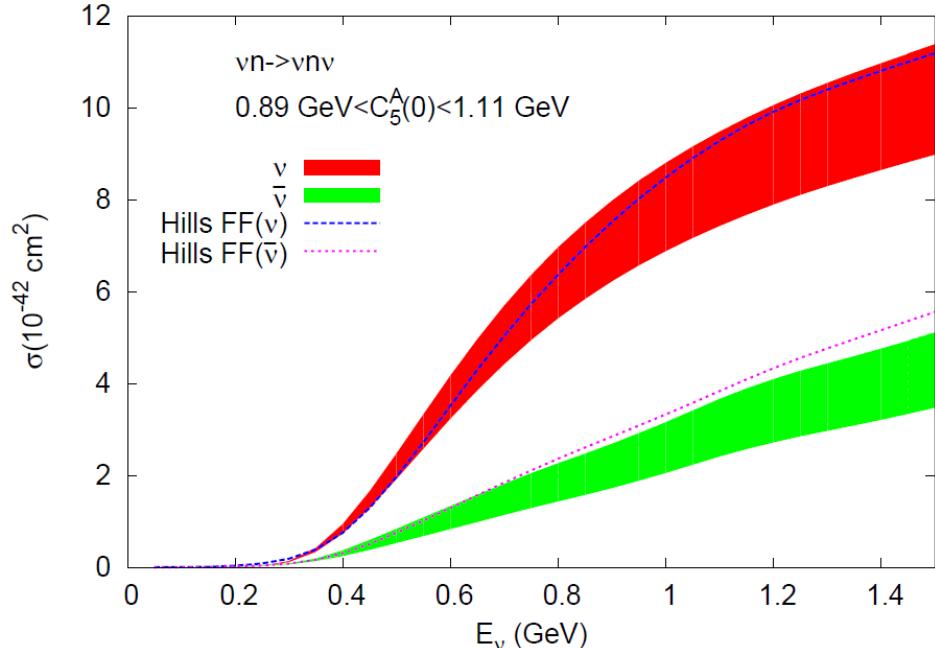
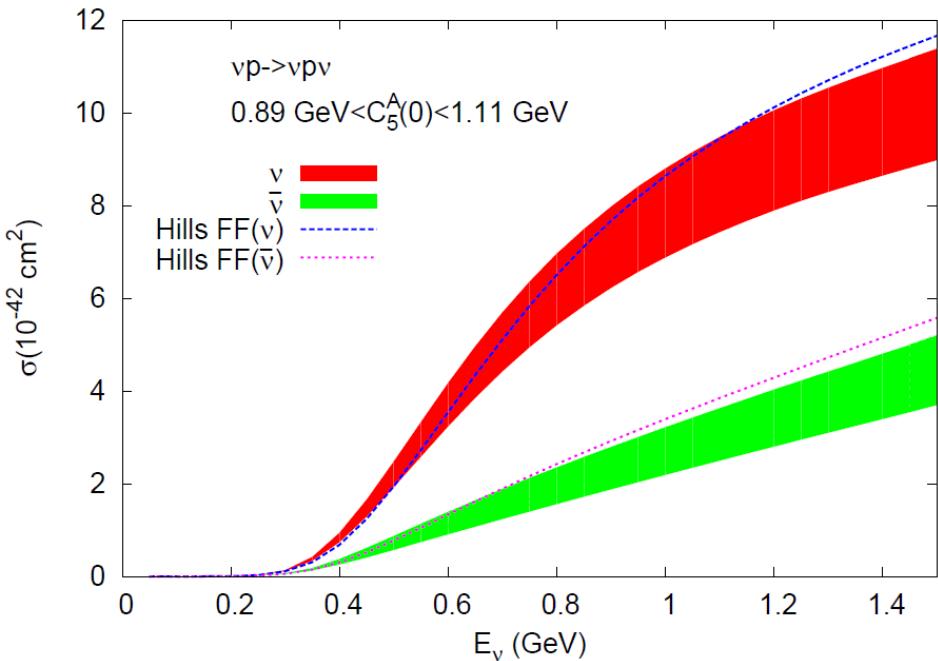
■ Error band: $C_A^5(0) = 1.00 \pm 0.11$ Hernandez et al., PRD 81 (2010)

Results on nucleons

Differential cross sections at $E_\nu = 1 \text{ GeV}$ ($E_\gamma > 140 \text{ MeV}$)



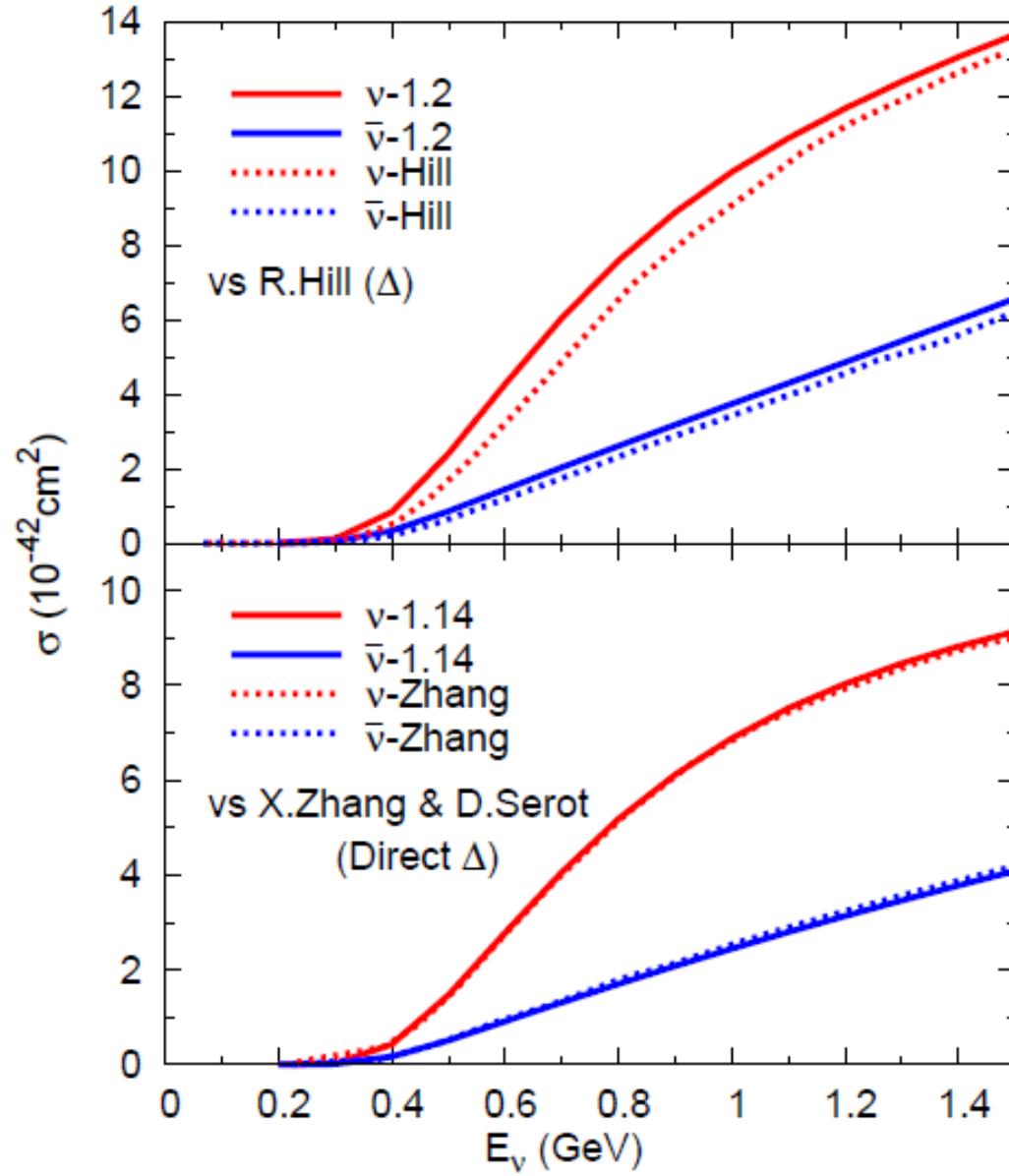
Comparison



- $N + \Delta$ only
- Error band: $C_5^A(0) = 1.00 \pm 0.11$ Hernandez et al., PRD 81 (2010)
- Main differences with R. Hill, PRD 81 (2010)
 - $C_5^A(0) = 1.00 \pm 0.11 \text{ GeV}$ vs 1.2
 - Energy dependent Γ_Δ vs $\Gamma_\Delta = \text{const} = 120 \text{ MeV}$
 - For nucleon pole diag.: $M_A = 1$ vs 1.2 GeV

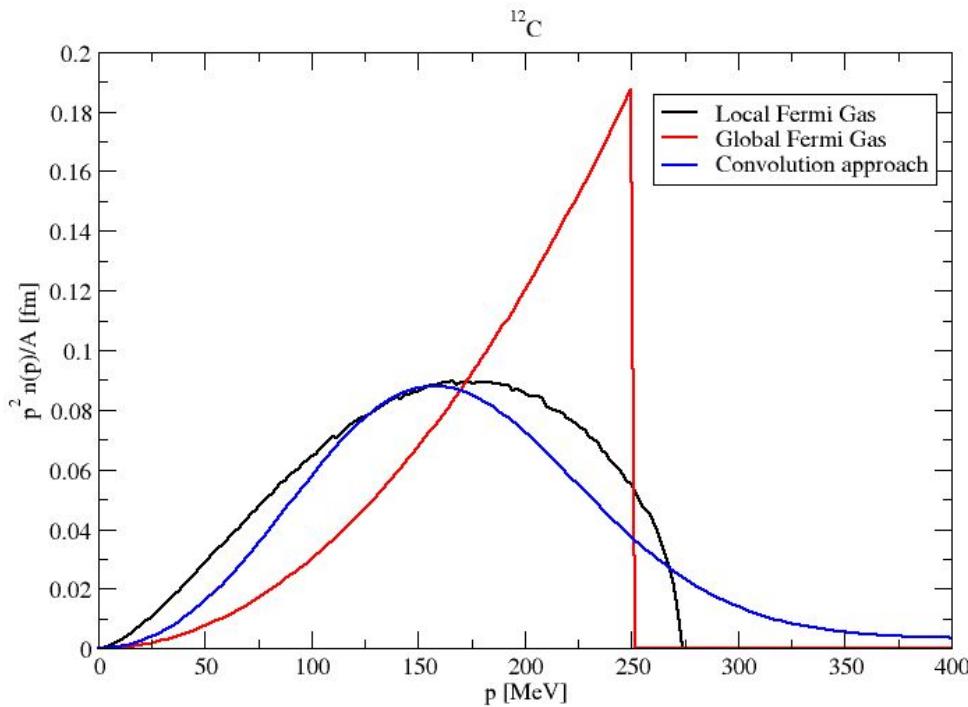
Comparison

- Only Δ
- $C_A^5(0) = 1.2$
- No cut in E_γ
- $C_A^5(0) = 1.14$
- $E_\gamma > 200 \text{ MeV}$



Nuclear effects

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$
- Relativistic Local Fermi Gas $p_F(r) = [\frac{3}{2}\pi^2\rho(r)]^{1/3}$
- Fermi motion $f(\vec{r}, \vec{p}) = \Theta(p_F(r) - |\vec{p}|)$
- Pauli blocking $P_{\text{Pauli}} = 1 - \Theta(p_F(r) - |\vec{p}|)$
- Free nucleons but with space-momentum correlations absent in the GFG



Convolution model:
Ciofi degli Atti, Simula, PRC 53 (1996)

Nuclear effects

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$
- In-medium modification of the $\Delta(1232)$ resonance

■ In
$$\frac{1}{p^2 - m_\Delta^2 + im_\Delta\Gamma_\Delta(p^2)}$$

replace $M_\Delta \rightarrow M_\Delta + \text{Re}\Sigma_\Delta(\rho)$

$$\frac{\Gamma_\Delta}{2} \rightarrow \frac{\tilde{\Gamma}_\Delta(\rho)}{2} - \text{Im}\Sigma_\Delta(\rho)$$

$\tilde{\Gamma}_\Delta \leftarrow$ Free width $\Delta \rightarrow N \pi$ modified by Pauli blocking

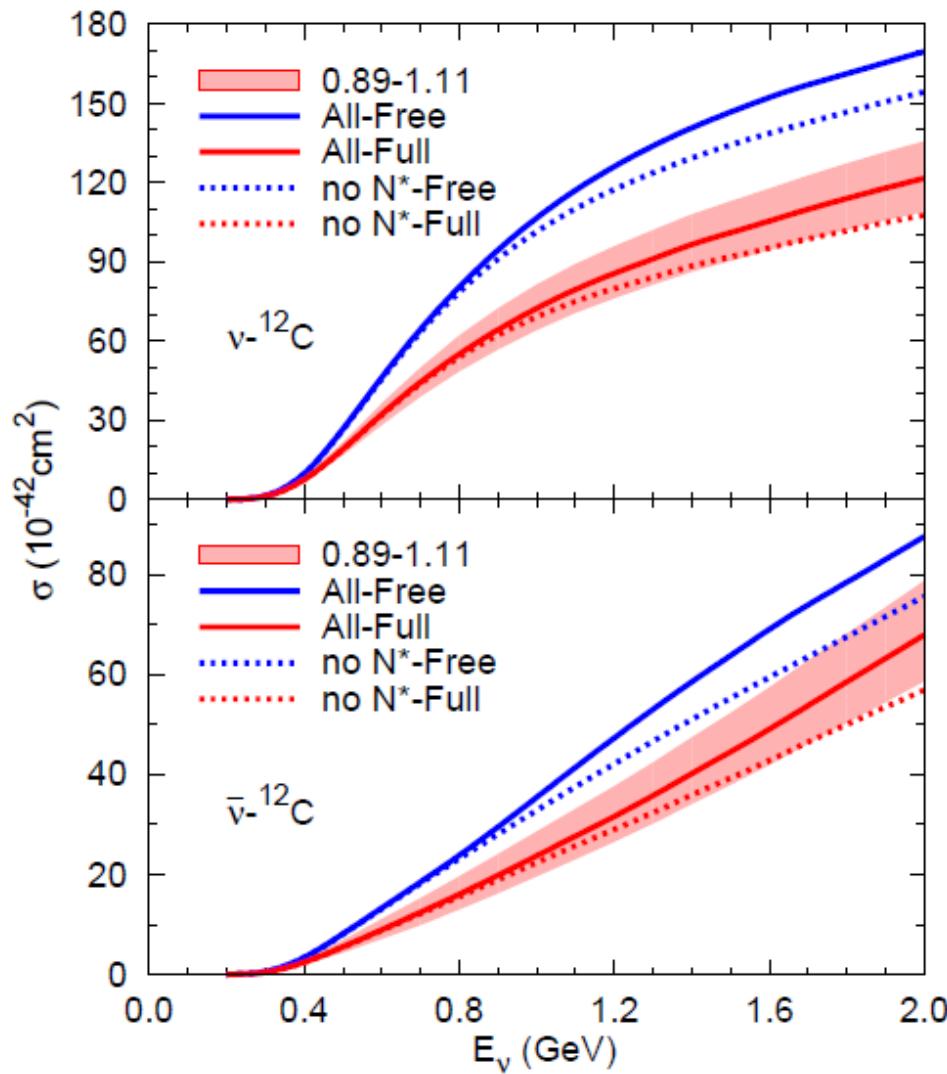
$$\text{Re}\Sigma_\Delta(\rho) \approx 0$$

$\text{Im}\Sigma_\Delta(\rho) \leftarrow$ many-body processes:

- $\Delta N \rightarrow N N$
- $\Delta N \rightarrow N N \pi$
- $\Delta N N \rightarrow N N N$

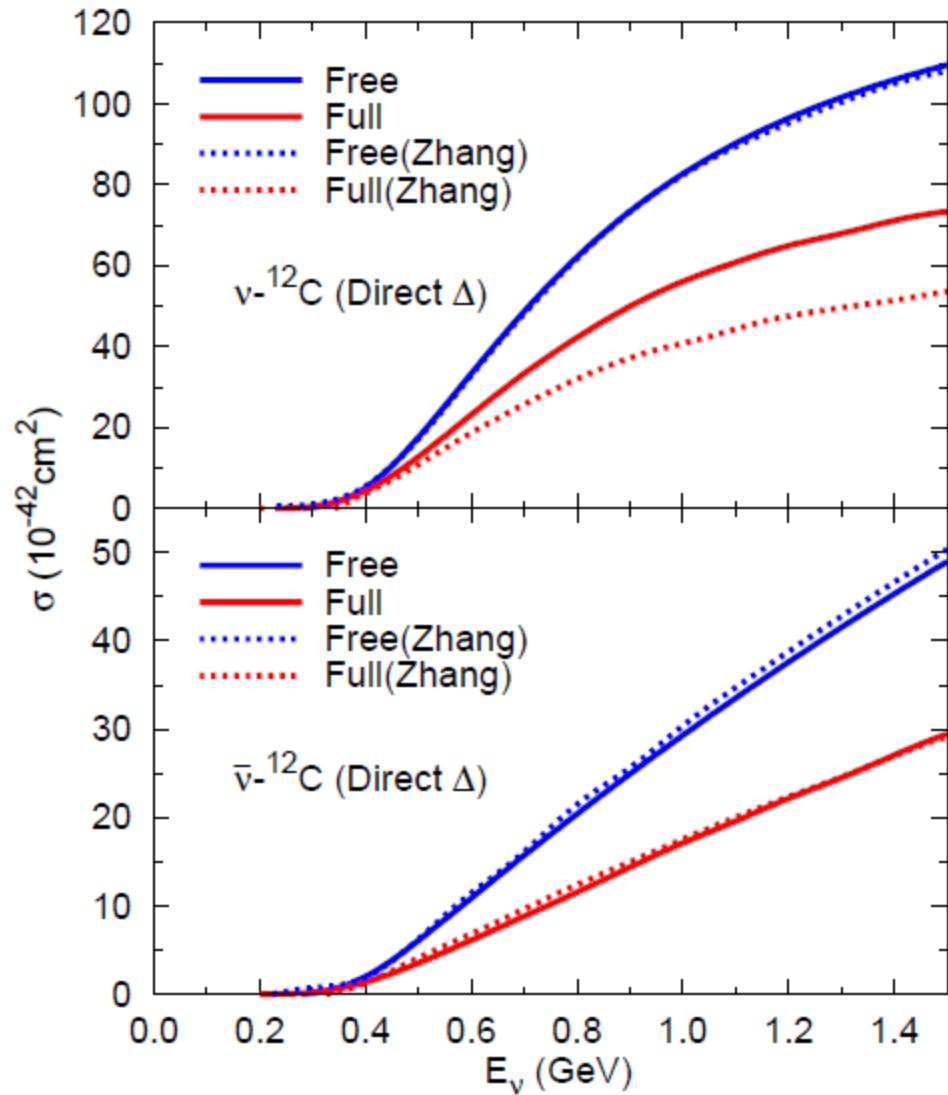
Results

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$
- Integrated cross section
- $E_\gamma > 140$ MeV
- Error band: $C^A_5(0) = 1.00 \pm 0.11$
- Considerable reduction caused by nuclear effects ($\sim 30\%$)



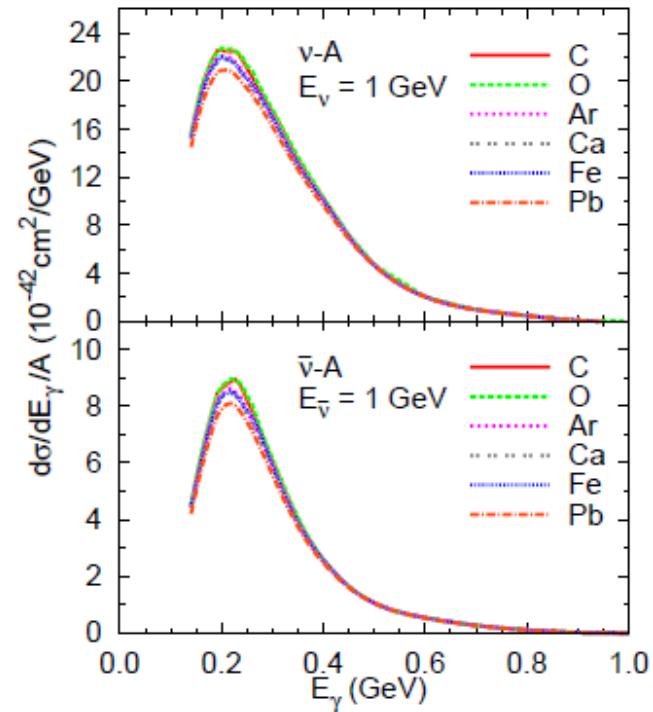
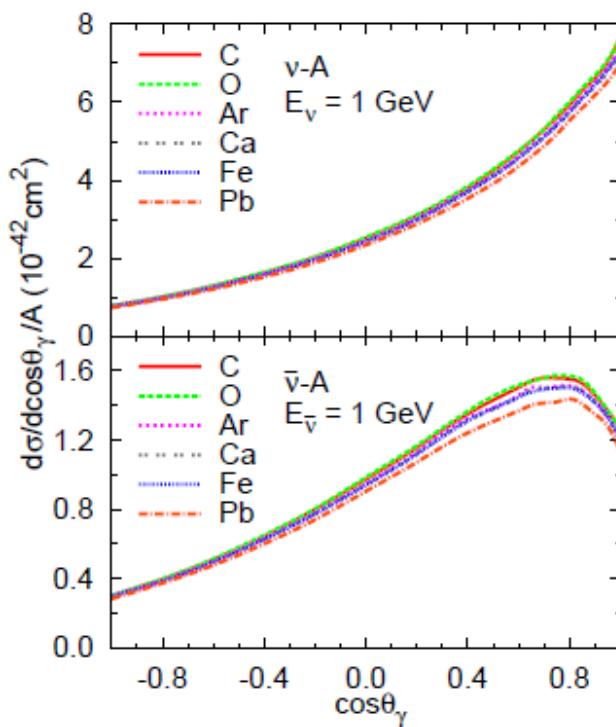
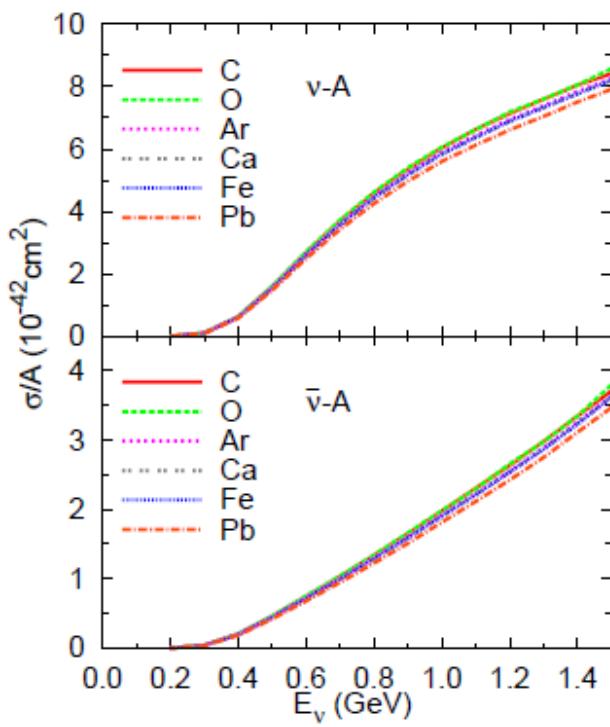
Comparison

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$
- Integrated cross section
- vs Zhang, Serot, PLB 719 (2013)
- Direct Δ only
- $E_\gamma > 200$ MeV
- $C_A^5(0) = 1.14$



Results

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$
- A dependence and differential cross sections at $E_\nu = 1 \text{ GeV}$
- $E_\gamma > 140 \text{ MeV}$



Coherent NC γ

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$
- Microscopic description:
 - Same NC γ mechanisms as in $\nu(\bar{\nu}) N \rightarrow \nu(\bar{\nu}) \gamma N$
 - $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$

- Nuclear corrections: $\Gamma_\Delta \rightarrow \tilde{\Gamma}_\Delta(\rho) - 2 \text{Im} \Sigma_\Delta(\rho)$
- Coherent sum over all nucleons

$$\mathcal{M}_r = \frac{G_F e}{\sqrt{2}} \epsilon_\mu^{*(r)} \bar{u}(p') \mathcal{A}^{\mu\alpha} u(p) l_\alpha$$

$$\mathcal{A}^{\mu\alpha} = \sum_{r=p,n} \int d\vec{r} e^{i(\vec{q}-\vec{q}_\gamma)\cdot\vec{r}} \rho_r(r) \hat{\Gamma}_r^{\mu\alpha}$$

$$\hat{\Gamma}_r^{\mu\alpha} = \frac{1}{2} \sum_i \text{Tr} \left[\bar{u} \Gamma_{i(r)}^\mu u \right] \leftarrow \text{sum over all mechanisms}$$

Coherent NC γ

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$
- Microscopic description:
 - Same NC γ mechanisms as in $\nu(\bar{\nu}) N \rightarrow \nu(\bar{\nu}) \gamma N$
 - $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$

- Nuclear corrections: $\Gamma_\Delta \rightarrow \tilde{\Gamma}_\Delta(\rho) - 2 \operatorname{Im} \Sigma_\Delta(\rho)$
- Coherent sum over all nucleons

$$\hat{\Gamma}_r^{\mu\alpha} = \frac{1}{2} \sum_i \operatorname{Tr} \left[\bar{u} \Gamma_{i(r)}^\mu u \right] \leftarrow \text{sum over all mechanisms}$$

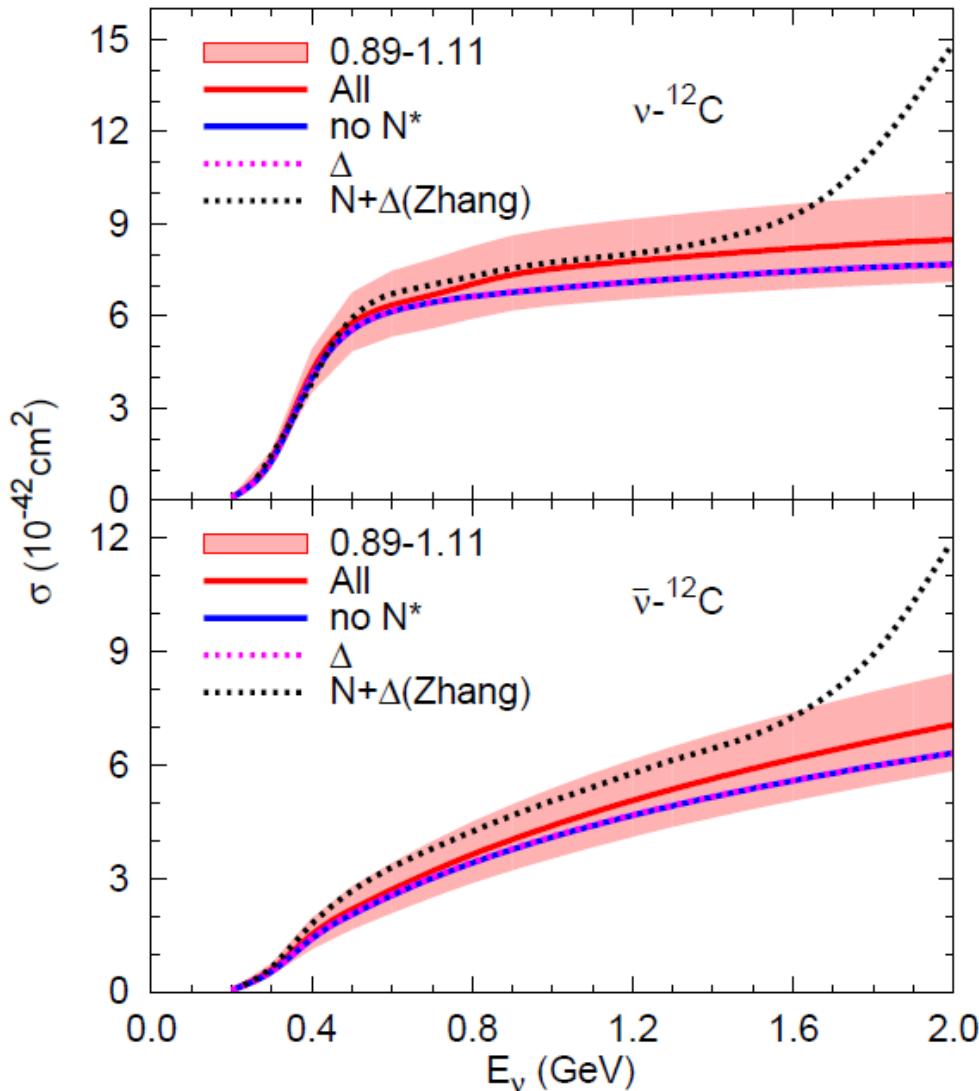
- Prescription for nucleon momenta:

$$p = \left(\sqrt{M^2 + \frac{1}{4} (\vec{q}_\gamma - \vec{q})^2}, \frac{\vec{q}_\gamma - \vec{q}}{2} \right) \quad p' = q - q_\gamma + p = \left(\sqrt{M^2 + \frac{1}{4} (\vec{q}_\gamma - \vec{q})^2}, -\frac{\vec{q}_\gamma - \vec{q}}{2} \right)$$

- equally shared by initial and final nucleons
- Δ momentum well defined (local treatment)

Results and Comparison

■ $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$

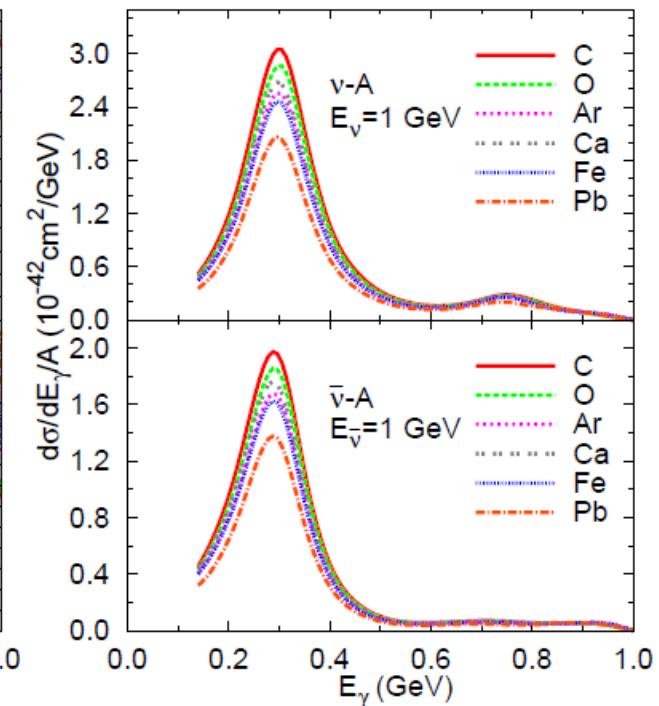
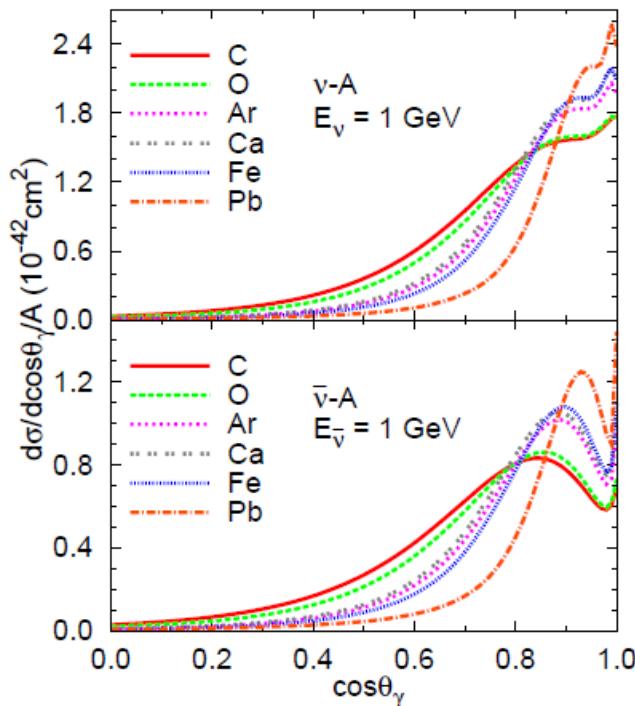
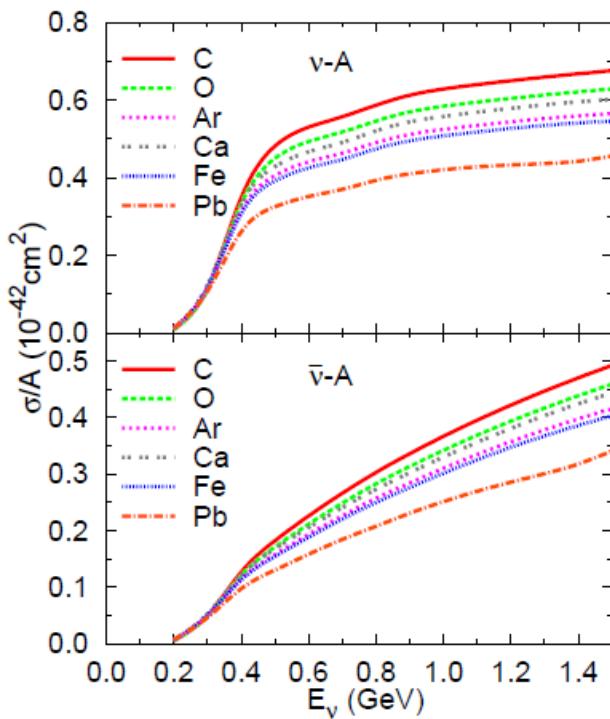


Results

■ $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$

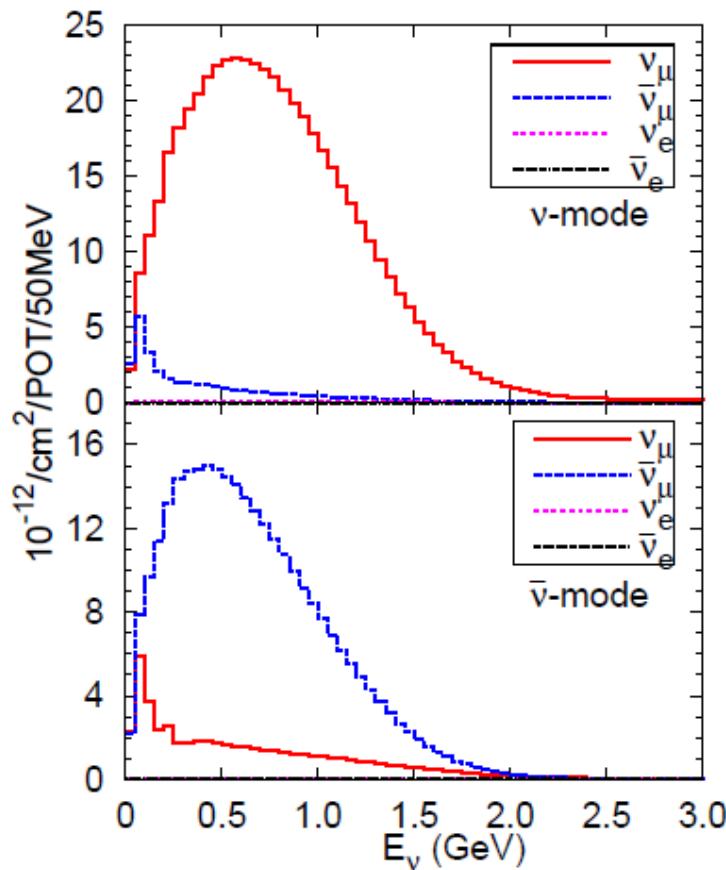
■ A dependence and differential cross sections at $E_\nu = 1 \text{ GeV}$

■ $E_\gamma > 140 \text{ MeV}$



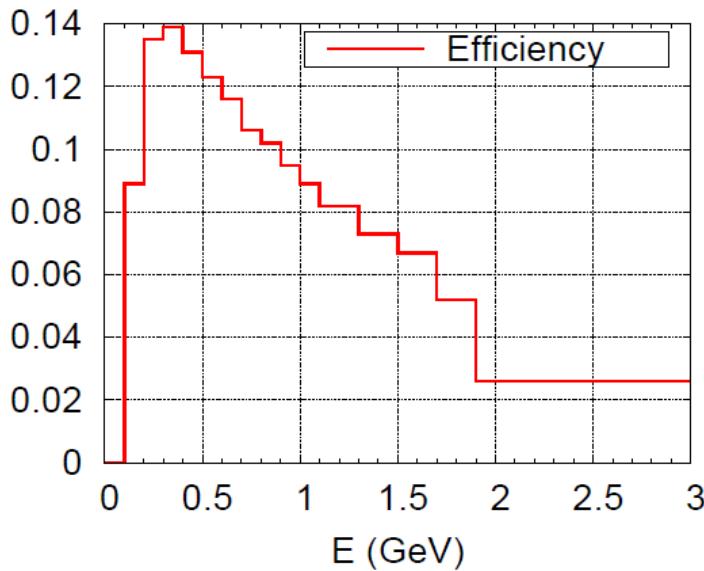
NC γ events at MiniBooNE

- Target: CH₂ Aguilar-Arevalo et al, PRL 110 (2013)
- Mass: 806 tons
- POT: 6.46×10^{20} (ν mode), 11.27×10^{20} ($\bar{\nu}$ mode)
- Fluxes: Aguilar-Arevalo et al, PRD 79 (2009)



NC γ events at MiniBooNE

- Target: CH₂ Aguilar-Arevalo et al, PRL 110 (2013)
- Mass: 806 tons
- POT: 6.46×10^{20} (ν mode), 11.27×10^{20} ($\bar{\nu}$ mode)
- Fluxes: Aguilar-Arevalo et al, PRD 79 (2009)
- E $_{\gamma}$ detection efficiency:
http://www-boone.fnal.gov/for_physicists/data_release/nue_nuebar_2012



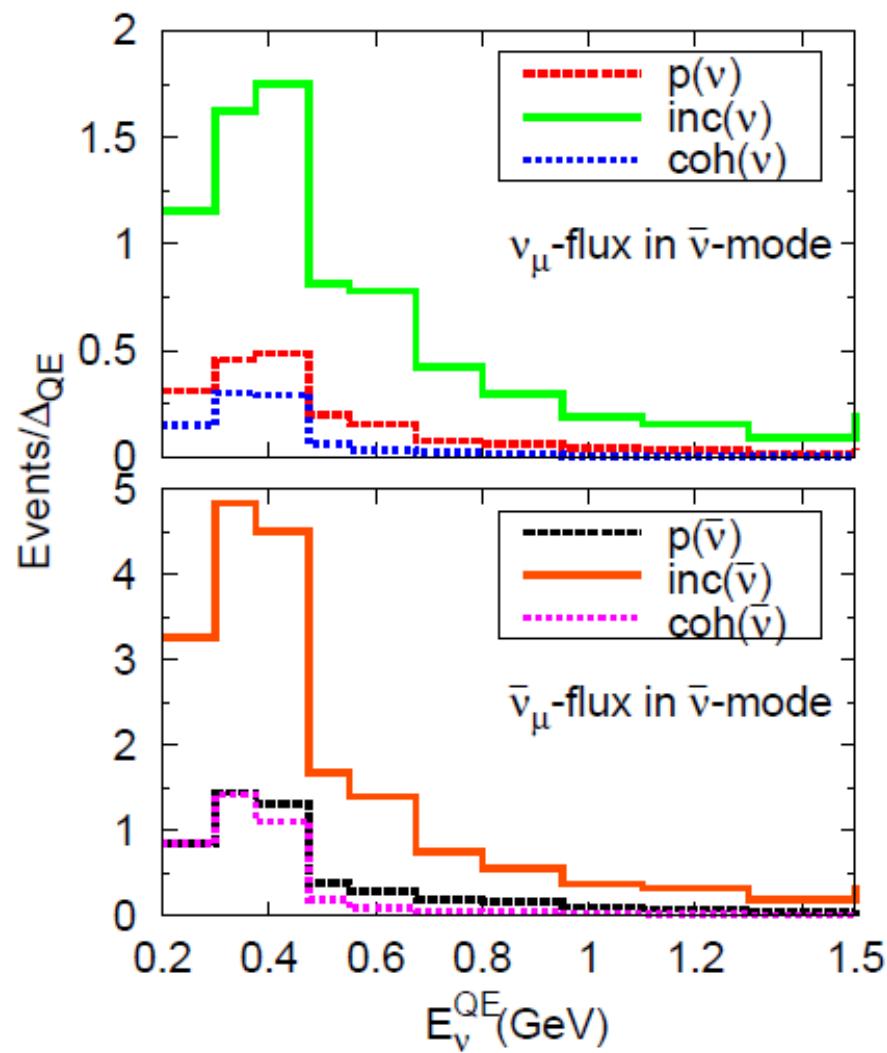
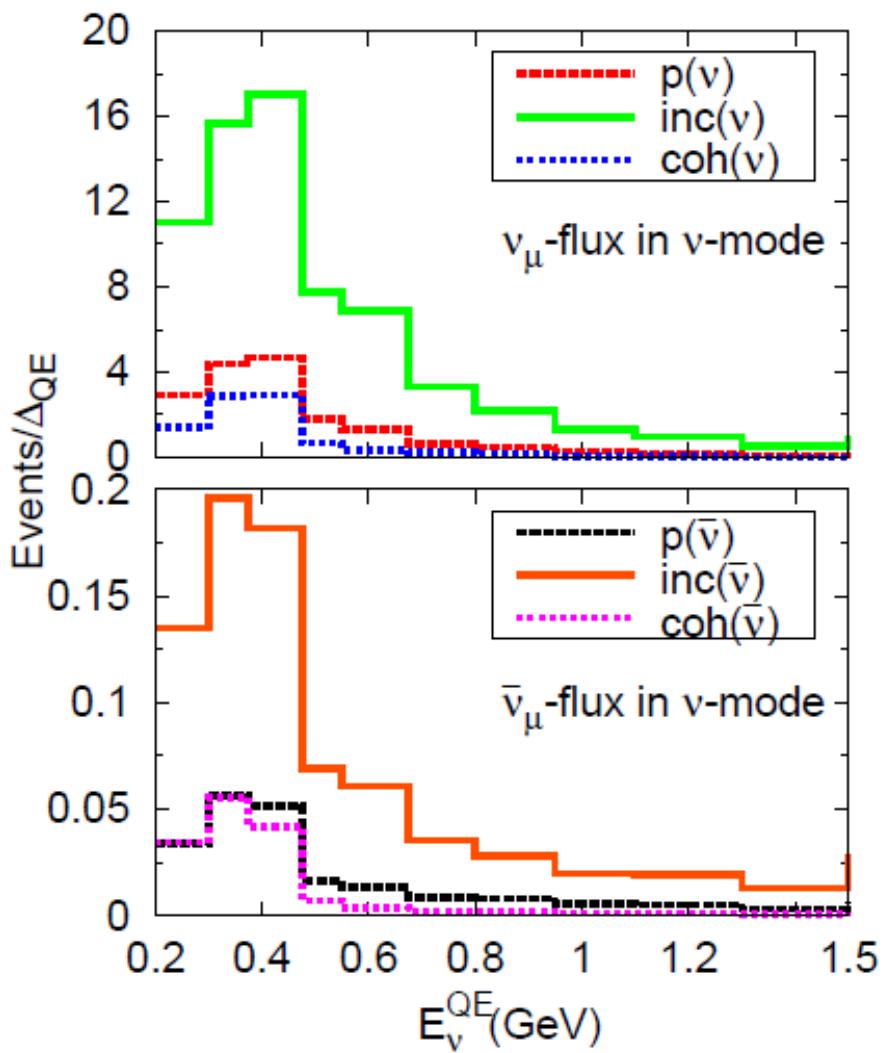
NC γ events

■ In the Lab. Frame:

$$\frac{dN}{dE_\gamma d\cos\theta_\gamma} = e(E_\gamma) \sum_{l=\nu_\mu, \bar{\nu}_\mu, \dots} N_{\text{POT}}^{(l)} \sum_{t=p, A} N_t \int dE_\nu \phi_l(E_\nu) \frac{d\sigma_{l t}(E_\nu)}{dE_\gamma d\cos\theta_\gamma}$$

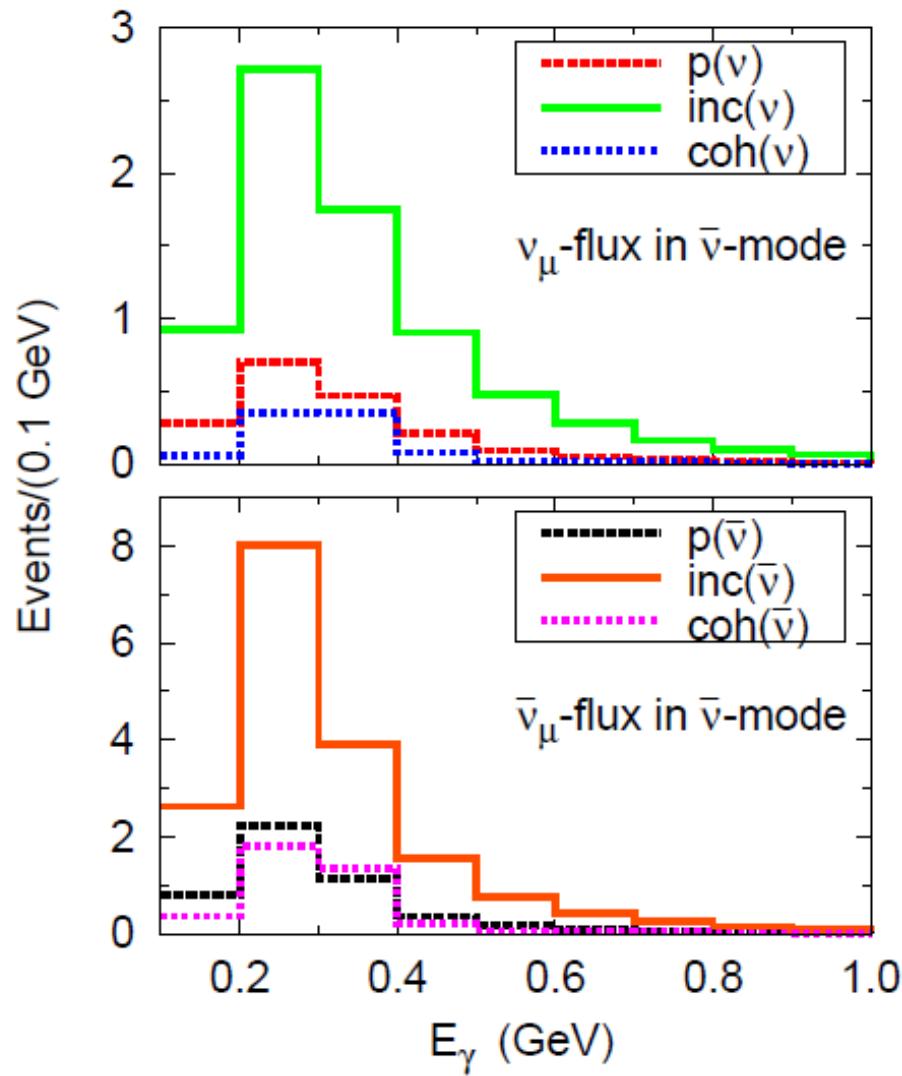
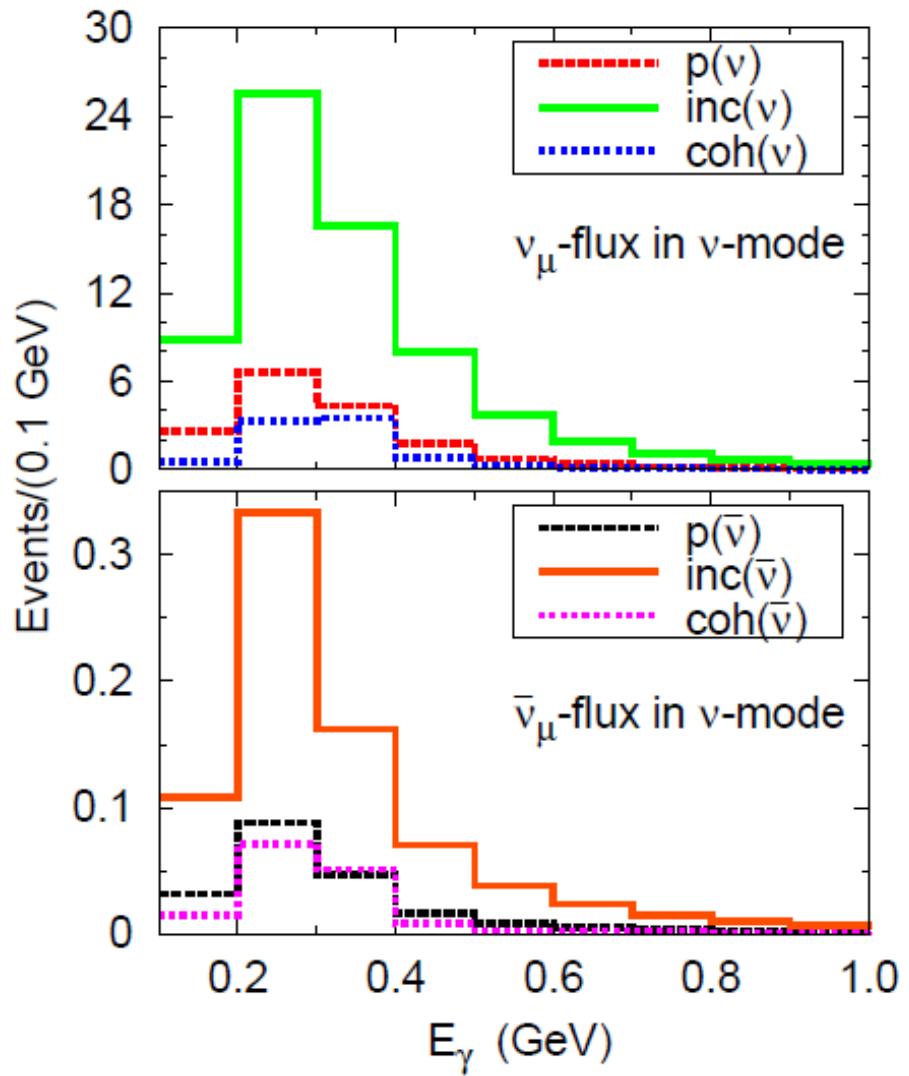
$$\frac{dN}{dE_\nu^{\text{QE}}} = \int dE_\gamma d\cos\theta_\gamma \frac{dN}{dE_\gamma d\cos\theta_\gamma} \delta \left(E_\nu^{\text{QE}} - \frac{2(m_N - E_B)E_\gamma - E_B^2 + 2m_N E_B}{2 [(m_N - E_B) - E_\gamma(1 - \cos\theta_\gamma)]} \right).$$

NC γ events at MiniBooNE

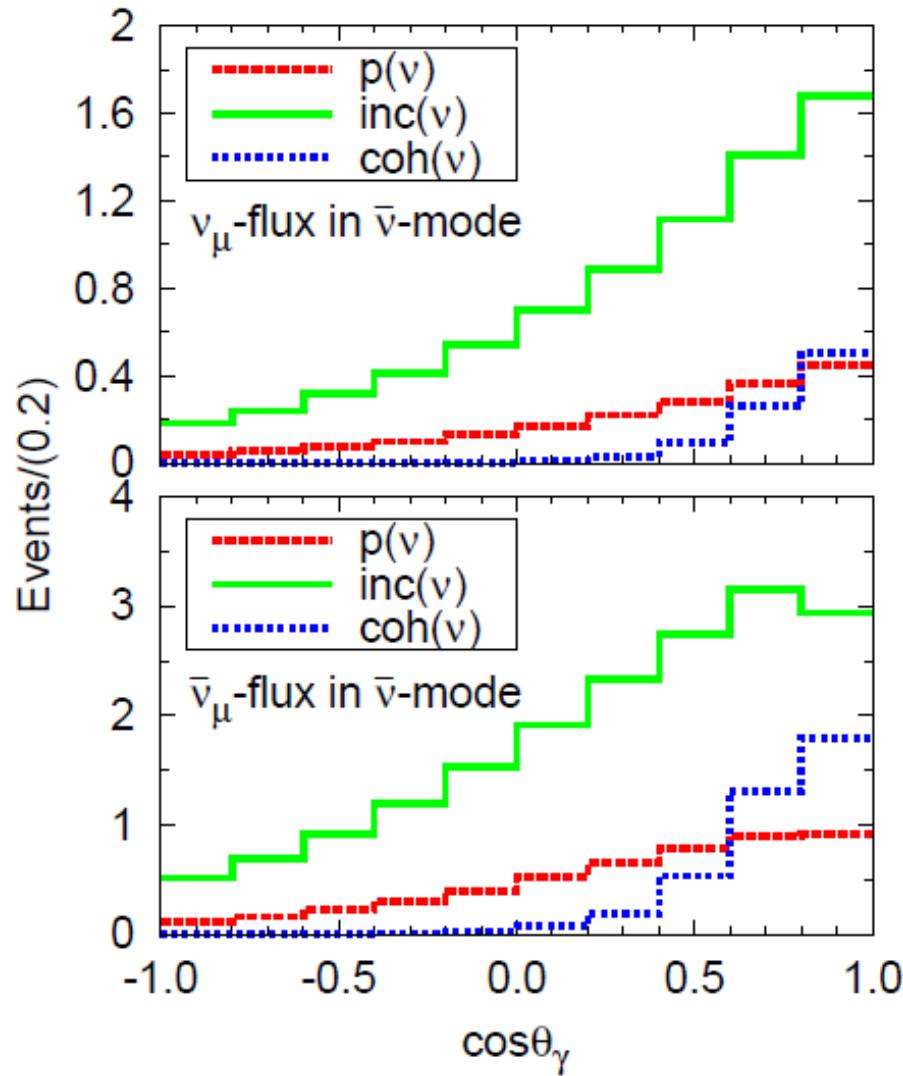
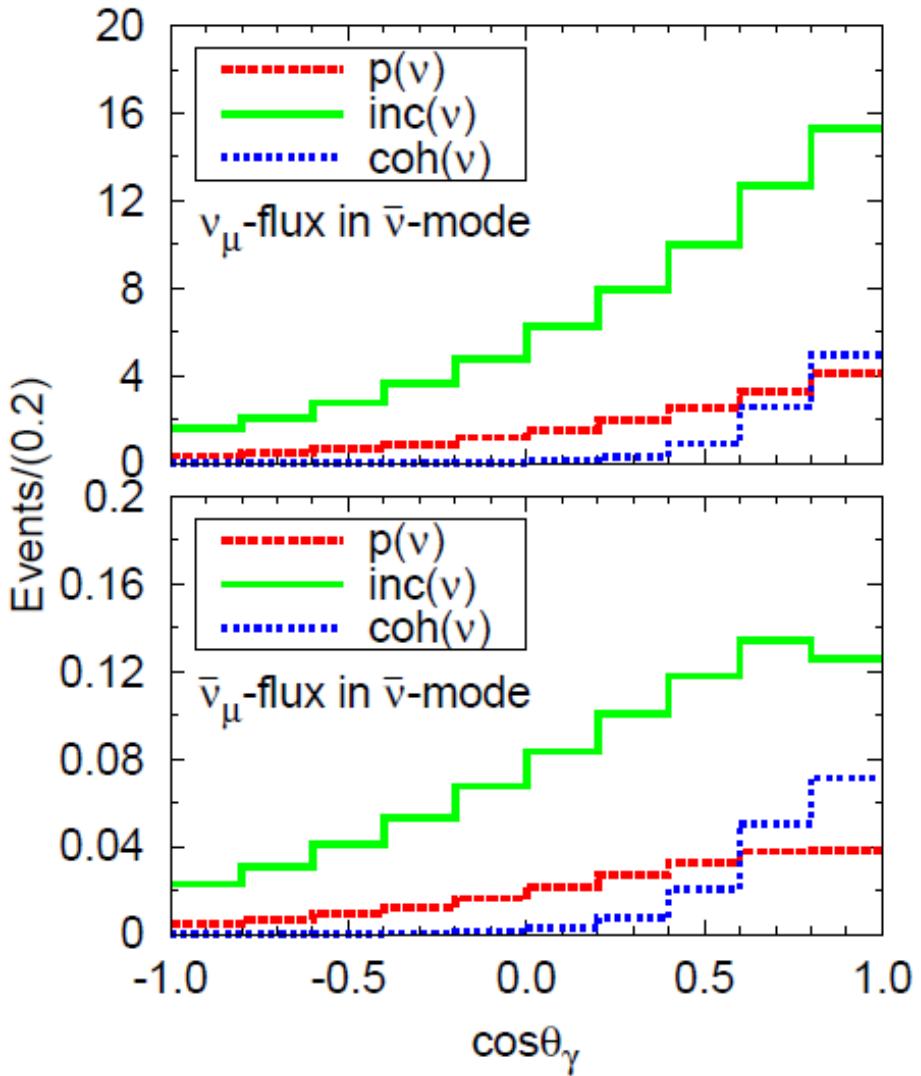


- 30-40 % of ν induced events in $\bar{\nu}$ mode

NC γ events at MiniBooNE

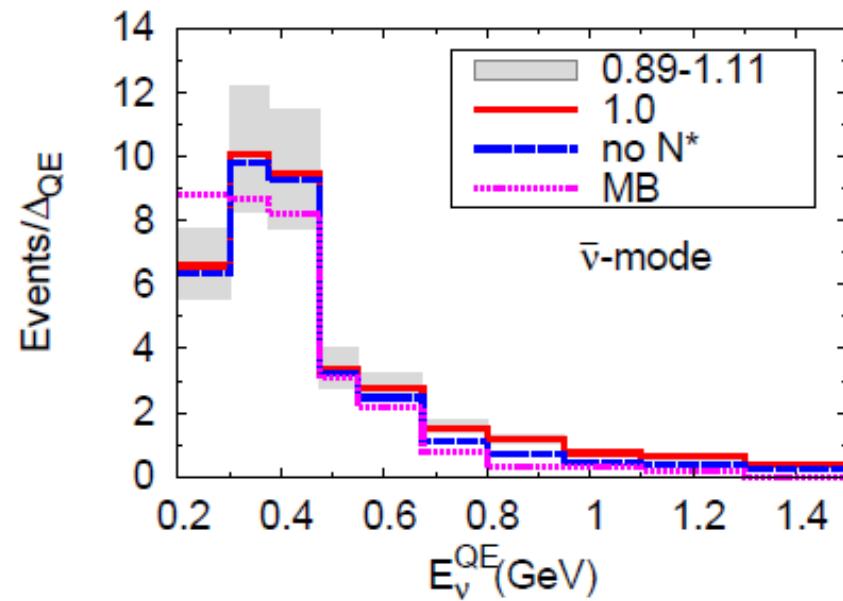
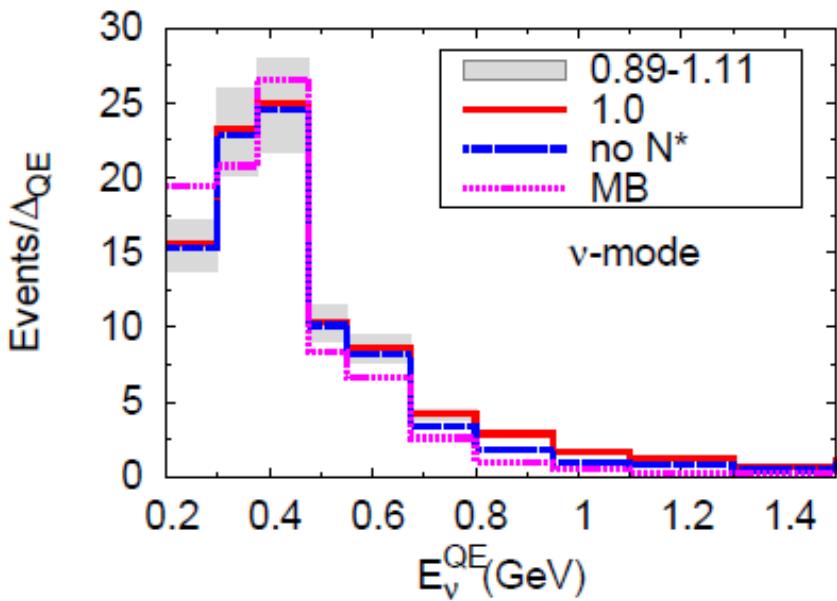


NC γ events at MiniBooNE



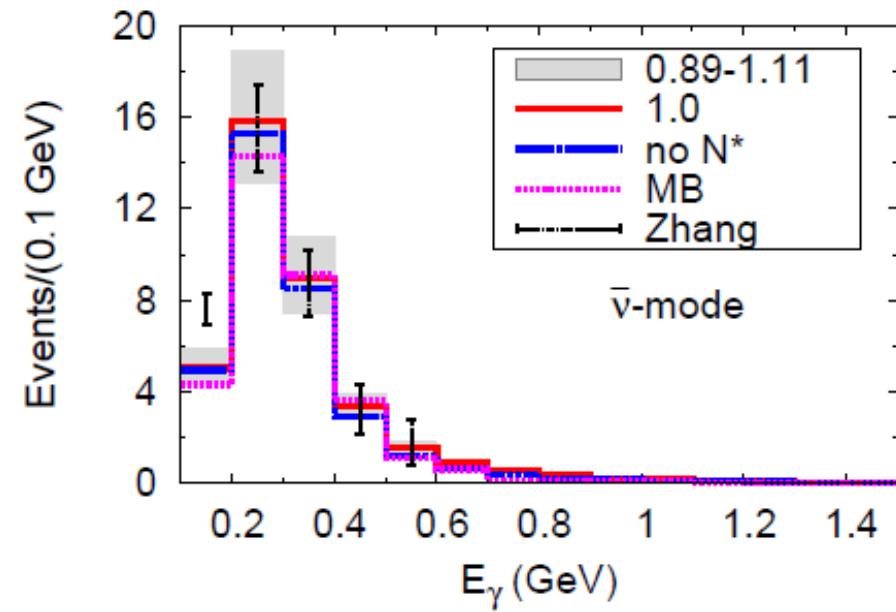
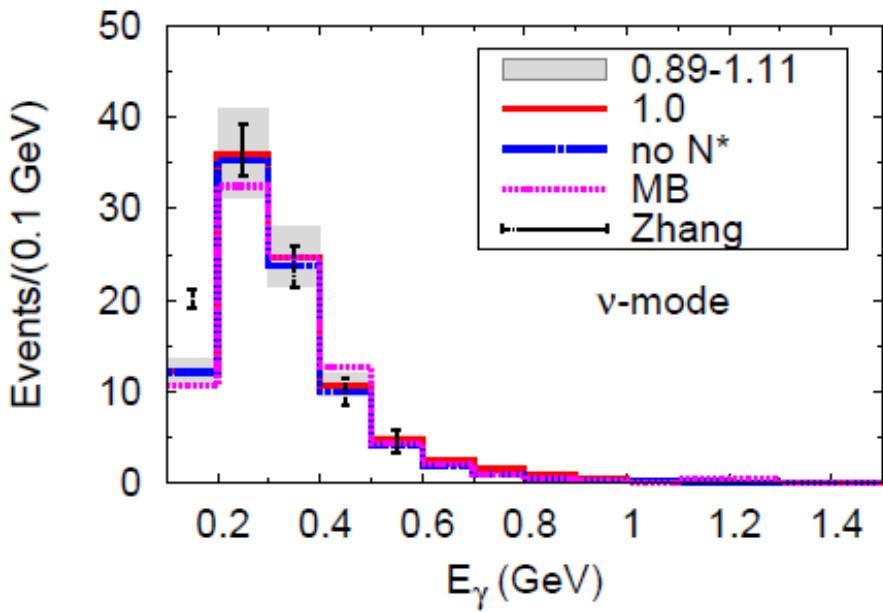
NC γ events at MiniBooNE

- Target: CH₂ Aguilar-Arevalo et al., PRL 110 (2013)
- Mass: 806 tons
- POT: 6.46×10^{20} (ν mode), 11.27×10^{20} ($\bar{\nu}$ mode)
- Fluxes: Aguilar-Arevalo et al, PRD 79 (2009)
- E $_{\gamma}$ detection efficiency:
http://www-boone.fnal.gov/for_physicists/data_release/nue_nuebar_2012
- Comparison to the MiniBooNE estimate



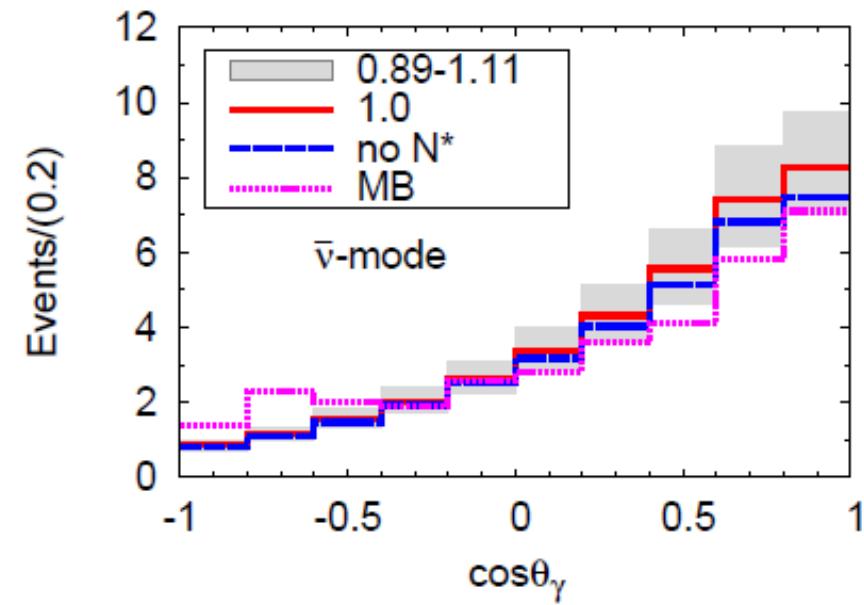
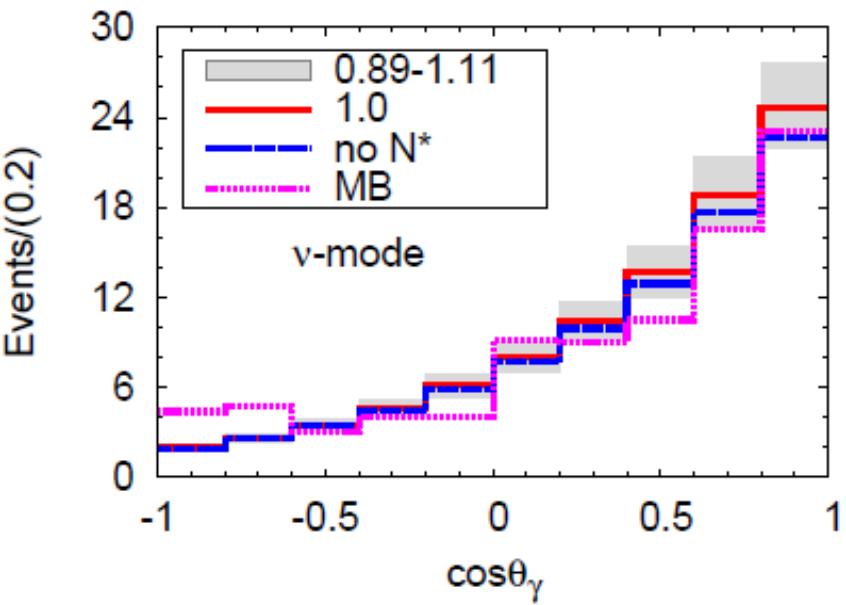
NC γ events at MiniBooNE

- Target: CH₂ Aguilar-Arevalo et al, PRL 110 (2013)
- Mass: 806 tons
- POT: 6.46×10^{20} (ν mode), 11.27×10^{20} ($\bar{\nu}$ mode)
- Fluxes: Aguilar-Arevalo et al, PRD 79 (2009)
- E_γ detection efficiency:
http://www-boone.fnal.gov/for_physicists/data_release/nue_nuebar_2012
- Comparison to the MiniBooNE estimate and to Zhang, Serot, PLB 719 (2013)



NC γ events at MiniBooNE

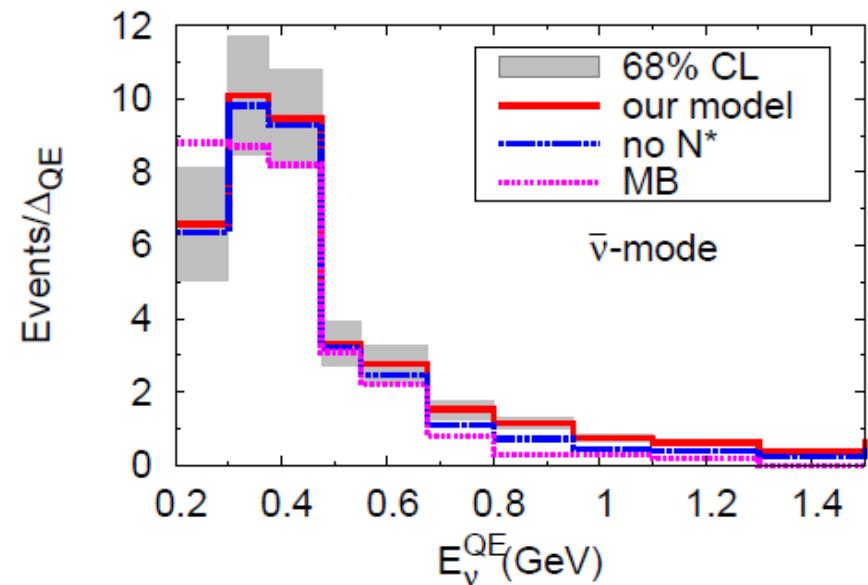
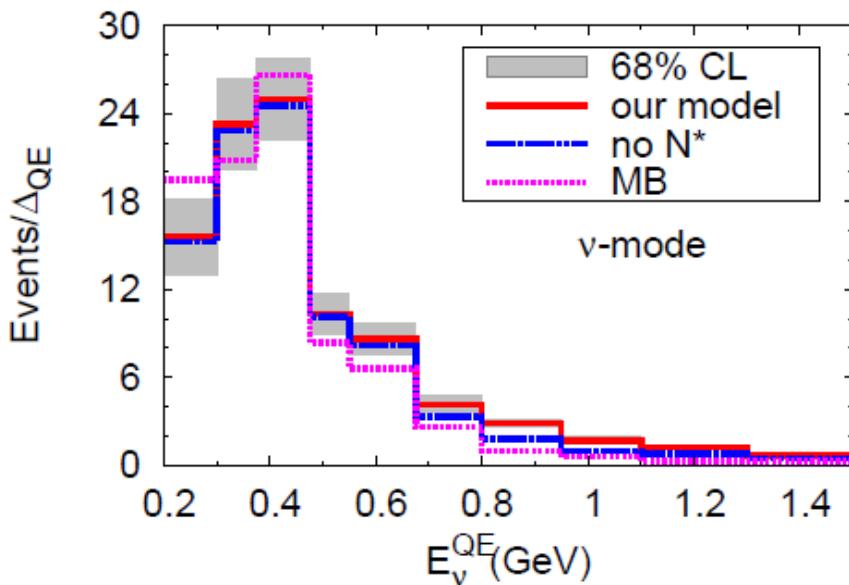
- Target: CH₂ Aguilar-Arevalo et al, PRL 110 (2013)
- Mass: 806 tons
- POT: 6.46×10^{20} (ν mode), 11.27×10^{20} ($\bar{\nu}$ mode)
- Fluxes: Aguilar-Arevalo et al, PRD 79 (2009)
- E_γ detection efficiency:
http://www-boone.fnal.gov/for_physicists/data_release/nue_nuebar_2012
- Comparison to the MiniBooNE estimate



NC γ events at MiniBooNE

■ Extended error budget

Quantity	Value
M_A	1.016 ± 0.026 GeV
$C_5^A(0)$	1.00 ± 0.11
$M_{A\Delta}$	0.93 ± 0.07 GeV
$A_{1/2}$	$(-140 \pm 6)10^{-3}$ GeV $^{-1/2}$
$A_{3/2}$	$(-265 \pm 5)10^{-3}$ GeV $^{-1/2}$
a_{HO}	1.692 ± 0.015 fm
α_{HO}	1.082 ± 0.001 fm
$(\text{Im}\Sigma_\Delta)r$	$r = 1.0 \pm 0.1$



NC γ events at MiniBooNE

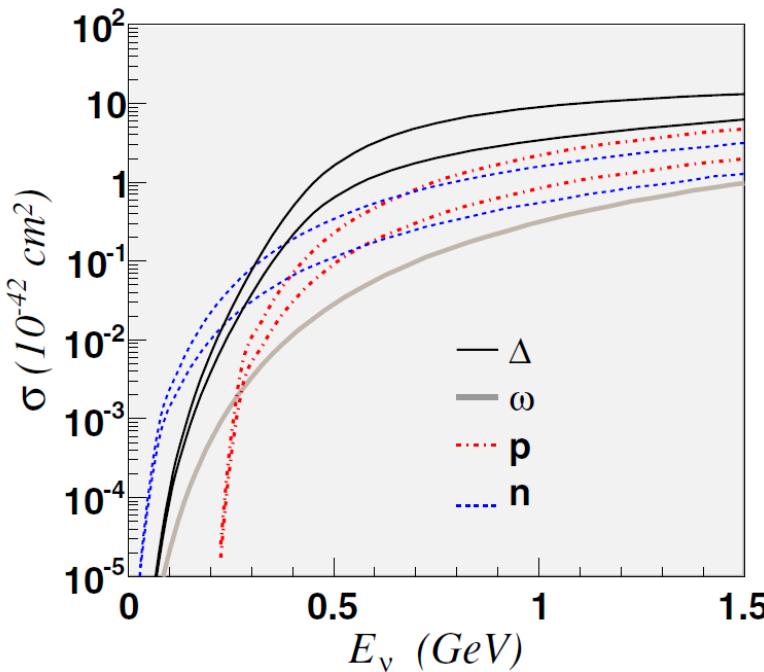
- Origin of e-like event excess @ MiniBooNE

- Unaccounted backgrounds?

- Higher order contributions

- involve unknown constants, couplings

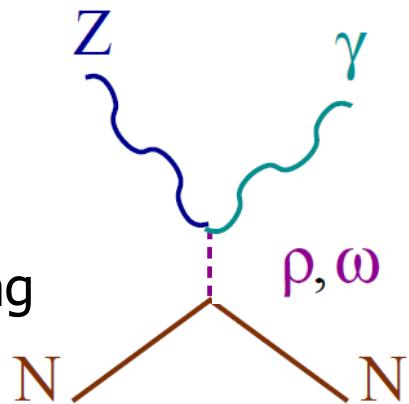
- ω favored: large (uncertain) isoscalar ωNN coupling



$$\nu(\bar{\nu}) N \rightarrow \nu(\bar{\nu}) \gamma N$$

R. Hill, PRD 81 (2010); 84 (2011)

- Very small

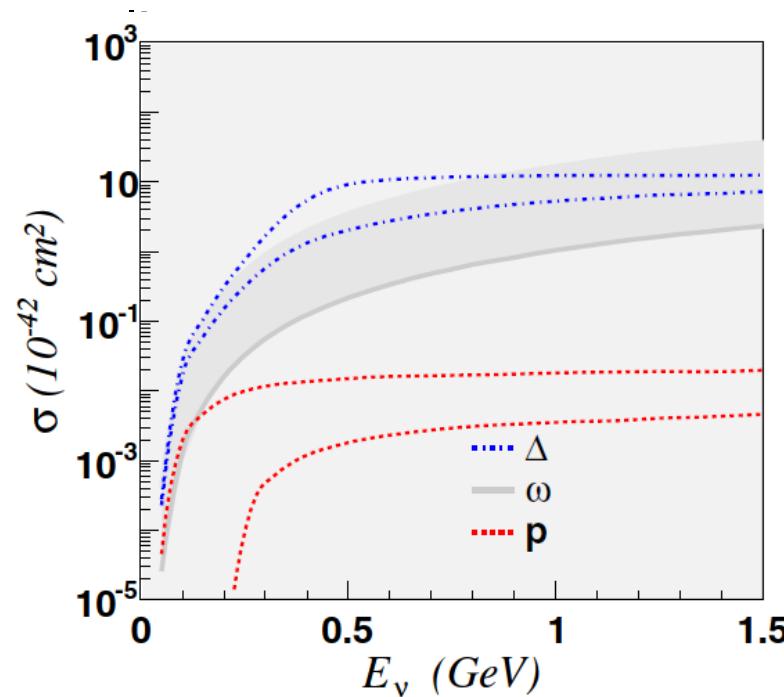


NC γ events at MiniBooNE

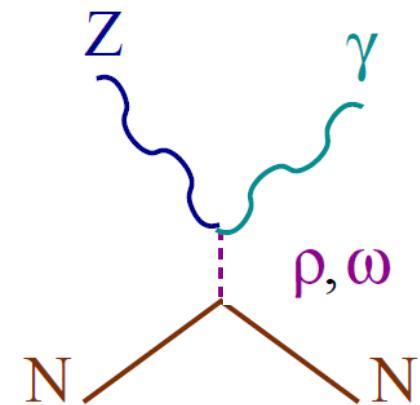
- Origin of e-like event excess @ MiniBooNE

- Unaccounted backgrounds?

- Higher order contributions
 - involve unknown constants, couplings
 - ω favored: large (uncertain) isoscalar ω



- Very small



$$\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$$

R. Hill, PRD 81 (2010); 84 (2011)

NC γ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE

- Unaccounted backgrounds?

- Higher order contributions

- involve unknown constants, couplings

- ω favored: large (uncertain) isoscalar ωNN coupling

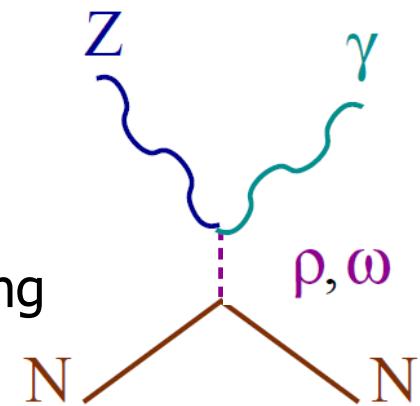
- Zhang & Serot

- Contact terms:

- negligible for $E_\nu < 550$ MeV

- rapidly growing with energy

- Careful: unitarity bounds (loops)



NC γ events at MiniBooNE

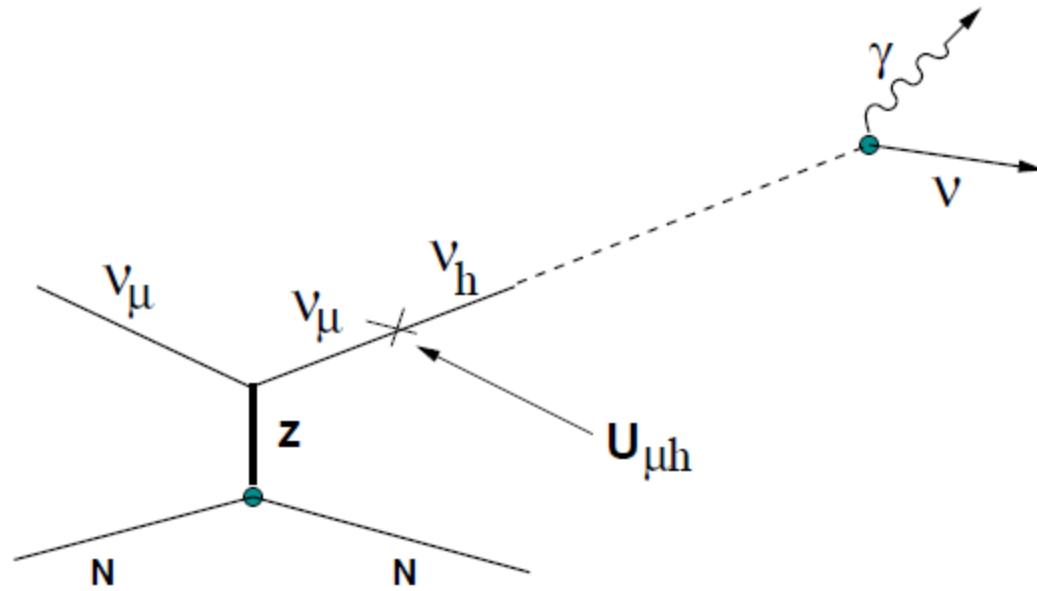
- Origin of e-like event excess @ MiniBooNE
 - Unaccounted backgrounds? No
- Multi-nucleon contributions
 - $Z \text{ } NN \rightarrow NN \pi$, $Z \text{ } NN \rightarrow NN \gamma$
 - Potentially important but unlikely to be the full solution

NC γ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
 - Oscillations: not explained by 1, 2, 3 families of sterile neutrinos
J. Conrad et al., Adv. High Energy Phys. 2013, C. Giunti et al., PRD88 (2013)
 - Lorentz violation T. Katori et al., PRD 74 (2006)
 - Heavy neutrinos S. Glinenko, PRL 103 (2009), M. Masip et al, JHEP 1301 (2013)

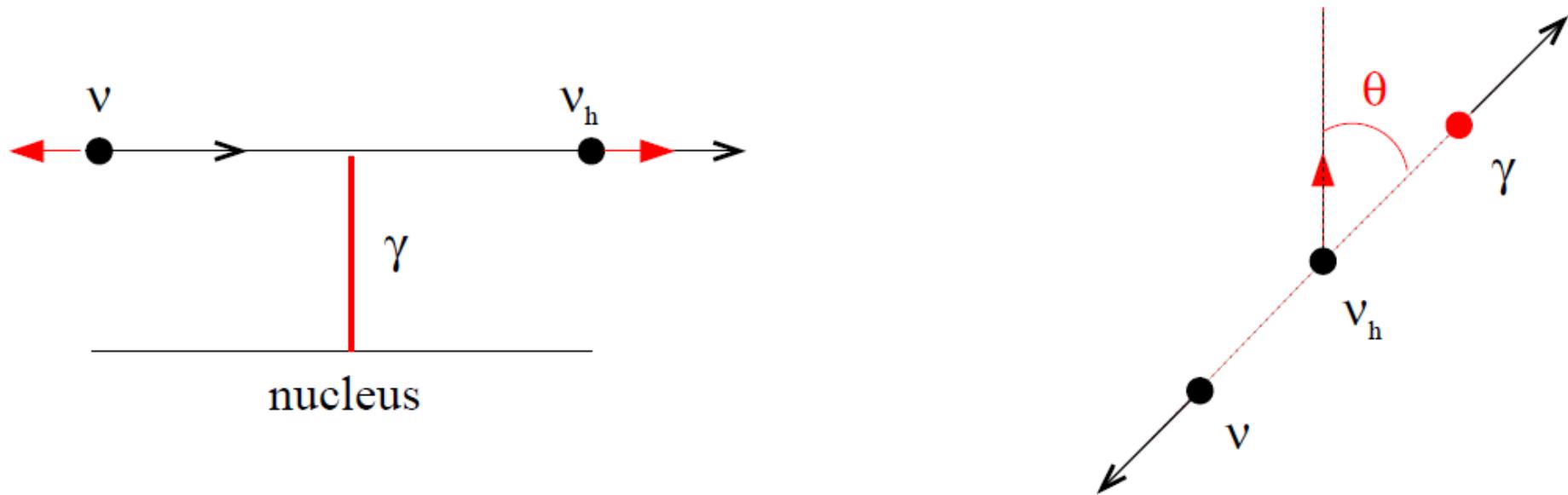
NC γ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
 - Oscillations: not explained by 1, 2, 3 families of sterile neutrinos
J. Conrad et al., Adv. High Energy Phys. 2013, C. Giunti et al., PRD88 (2013)
 - Lorentz violation T. Katori et al., PRD 74 (2006)
 - Heavy neutrinos S. Glinenko, PRL 103 (2009), M. Masip et al, JHEP 1301 (2013)



NC γ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
 - Oscillations: not explained by 1, 2, 3 families of sterile neutrinos
J. Conrad et al., Adv. High Energy Phys. 2013, C. Giunti et al., PRD88 (2013)
 - Lorentz violation T. Katori et al., PRD 74 (2006)
 - Heavy neutrinos S. Glinenko, PRL 103 (2009) , M. Masip et al, JHEP 1301 (2013)



NC γ events at NOMAD

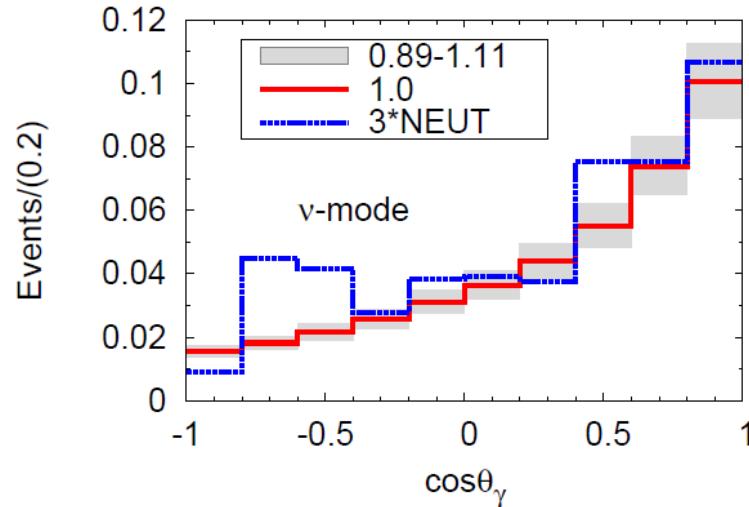
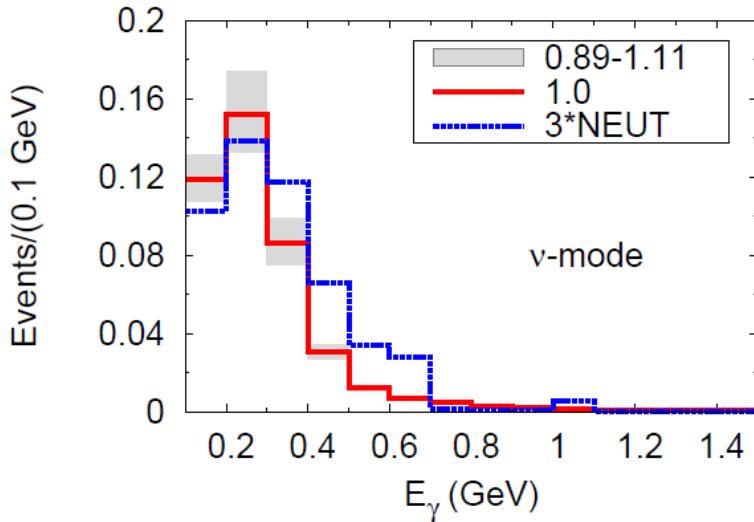
- Kullenberg et al., PLB 706 (2012)

$$\frac{\sigma(\text{NC}\gamma)}{\sigma(\nu_\mu A \rightarrow \mu^- X)} < 4.0 \times 10^{-4} \quad \text{at 90 \% CL}$$

- Constraint to models attempting to explain the MiniBooNE anomaly (γ)
- In our case:
 - $W\gamma_N < 1.6 \text{ GeV}$
 - Up to the extent that high q^2 extrapolations of the FF can be trusted
 - Neglecting nuclear effects

$$\frac{\sigma(\text{NC}\gamma, W_{\gamma N} 1.6 \text{ GeV})}{\sigma(\nu_\mu A \rightarrow \mu^- X)} \approx 0.8 \times 10^{-4} \quad \text{at } E_\nu = 25 \text{ GeV}$$

NC γ events at T2K



$$N_{\text{tot}} = 0.421 \pm 0.051 \quad \text{vs} \quad N_{\text{NEUT}} = 0.165$$

- Does this **discrepancy** come from the **NEUT** vs **Wang et al.** cross sections?

NC γ events at T2K

Targ

Mas:

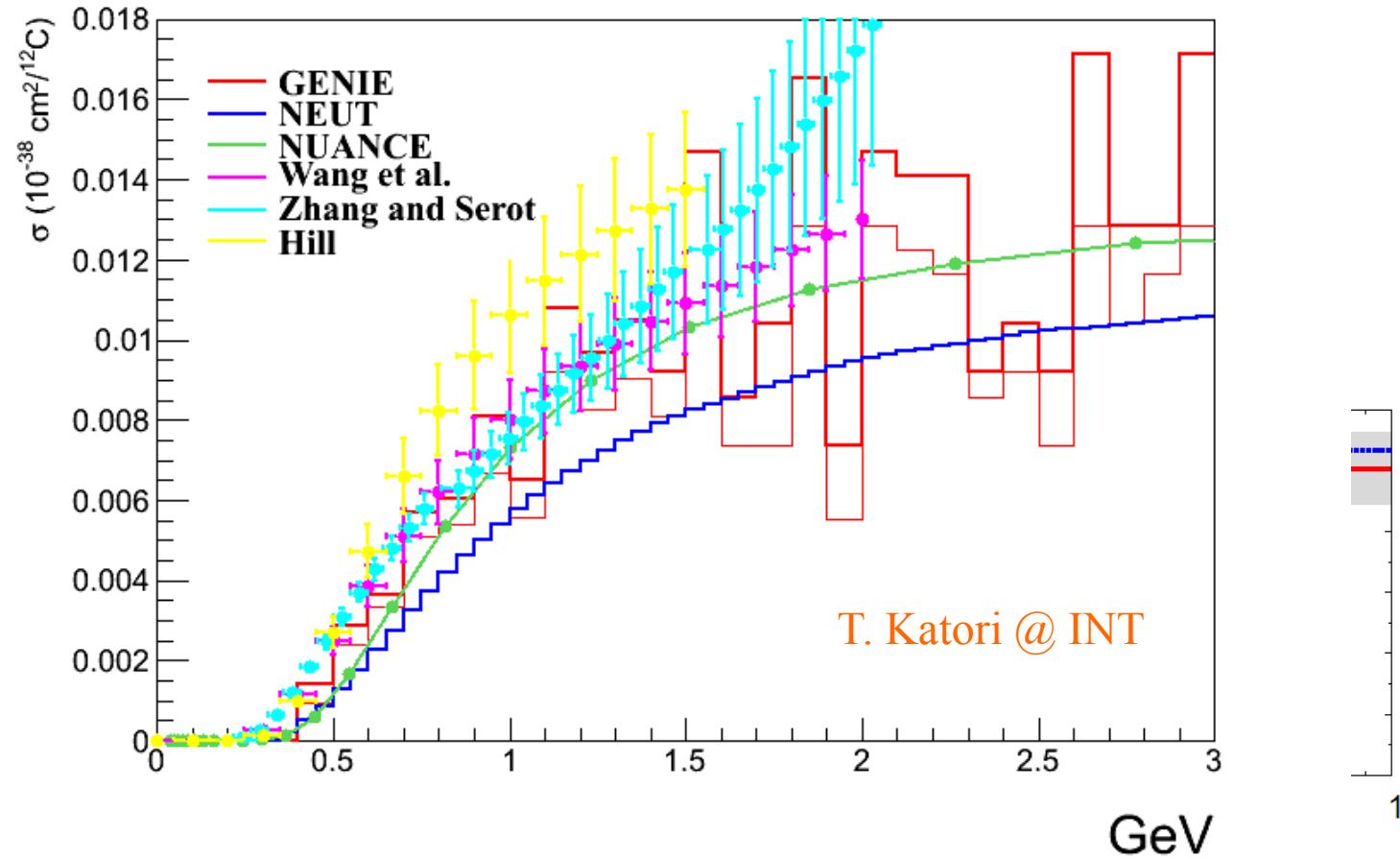
POT

Flux

No C

Com

Events/(0.1 GeV)



$$N_{\text{tot}} = 0.421 \pm 0.051 \text{ vs } N_{\text{NEUT}} = 0.165$$

Does this **discrepancy** come from the NEUT vs Wang et al. cross sections?

NC γ events at T2K

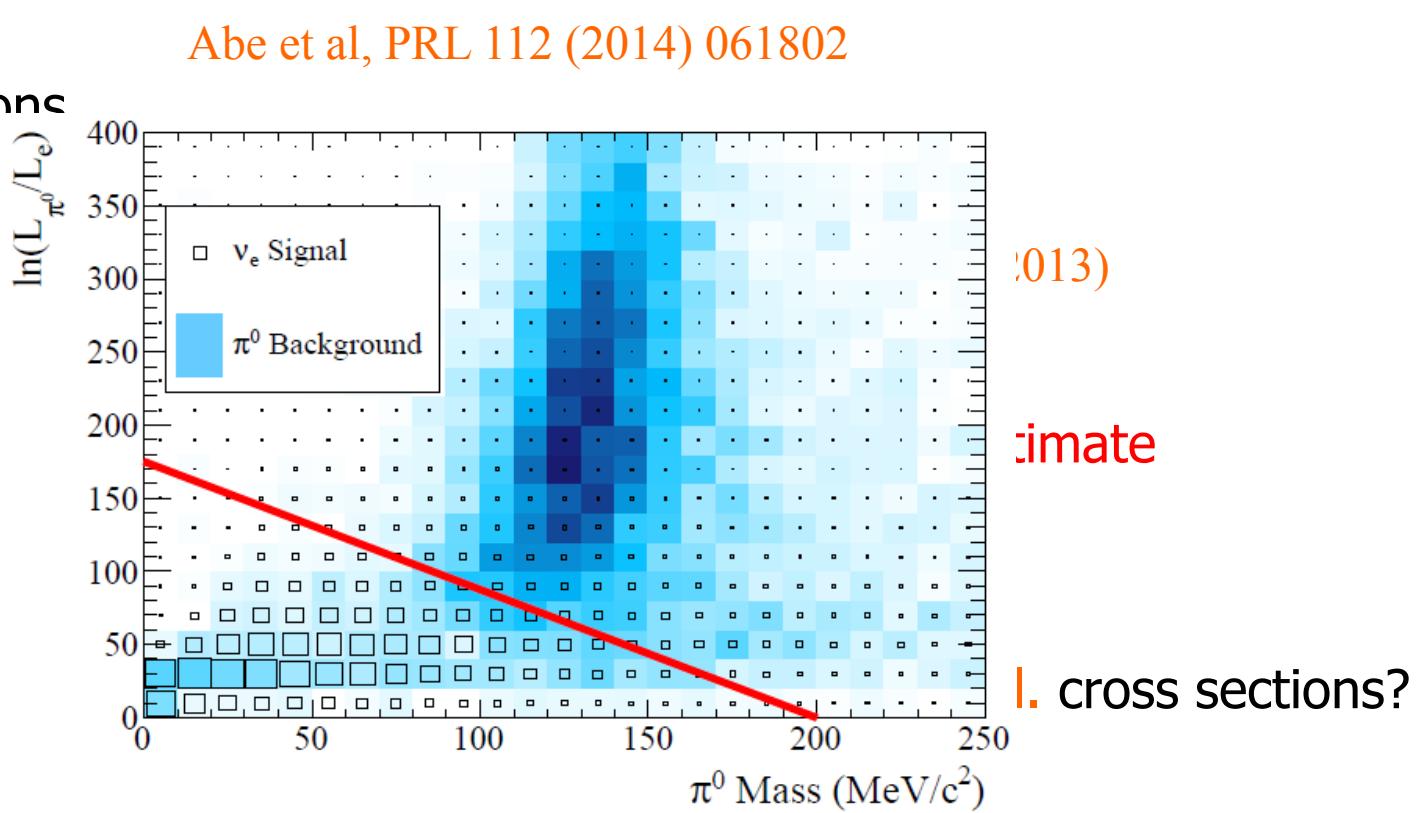
$$N_{\text{tot}} = 0.421 \pm 0.051 \quad \text{vs} \quad N_{\text{NEUT}} = 0.165$$

- Does this **discrepancy** come from the NEUT vs Wang et al. cross sections?
 - At least in part: YES
 - Does this **discrepancy** matter?
 - For θ_{13} ? probably not.

NC γ events at T2K

- Target: H₂O
- Mass: 22.5 kton e
- POT: 6.57×10^{21} $\text{cm}^{-2}\text{s}^{-1}$
- Fluxes: SK250
- No detection $\epsilon = 0.01$
- Comparison to neutrino flux

$$N_{\text{tot}} = 0.4$$



- Does this **discrepancy** matter?
 - At least in I. cross sections?
- Does this **discrepancy** matter?
 - For θ_{13} ? probably not.
 - Better π^0 rejection cut \Rightarrow NC γ relatively more important

NC γ events at T2K

- Target: H₂O Abe et al, PRL 112 (2014) 061802
 - Mass: 22.5 ktons
 - POT: 6.57×10^{20} (ν mode)
 - Fluxes: SK250 $100 \text{ MeV} < E_\nu < 3 \text{ GeV}$ Abe et al, PRD 87 (2013)
 - No detection efficiency
 - Comparison to T2K (H. Tanaka, S. Tobayama / NEUT) estimate

$$N_{\text{tot}} = 0.421 \pm 0.051 \quad \text{vs} \quad N_{\text{NEUT}} = 0.165$$

- Does this **discrepancy** come from the NEUT vs Wang et al. cross sections?
 - At least in part: YES
 - Does this **discrepancy** matter?
 - For θ_{13} ? probably not.
 - Better π^0 rejection cut \Rightarrow NC γ relatively more important
 - For CP violation searches? perhaps...

Conclusions

- We have studied **photon** emission induced by **NC** interactions with nucleons and nuclei at $E_\nu \sim 1$ GeV
- Reaction dominated by $\Delta(1232)$ excitation
- **Theoretical error** dominated by **N**- Δ axial transition properties
- Large ($\sim 30\%$) reduction on the cross section due to **nuclear effects**
- Results consistent with **MiniBooNE's** estimate (in line with **Zhang, Serot, PLB 719**).
- NC_γ : **insufficient** to explain the **excess** of e-like events at **MiniBooNE**
- Implications for **T2K** discussed: 2.5 more NC_γ events predicted.
- **NOMAD** limit respected
- Details in:
 - E. Wang, LAR, J. Nieves, PRC 89 (2014) 015503
 - E. Wang, LAR, J. Nieves, arXiv:1407.6060

Coherent NC γ

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$
- Microscopic description:
 - Same NC γ mechanisms as in $\nu(\bar{\nu}) N \rightarrow \nu(\bar{\nu}) \gamma N$
 - $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X$

- Nuclear corrections: $\Gamma_\Delta \rightarrow \tilde{\Gamma}_\Delta(\rho) - 2 \text{Im} \Sigma_\Delta(\rho)$
- Coherent sum over all nucleons

$$\hat{\Gamma}_r^{\mu\alpha} = \frac{1}{2} \sum_i \text{Tr} \left[\bar{u} \Gamma_{i(r)}^\mu u \right] \leftarrow \text{sum over all mechanisms}$$

- Prescription for nucleon momenta:

$$p = \left(\sqrt{M^2 + \frac{1}{4} (\vec{q}_\gamma - \vec{q})^2}, \frac{\vec{q}_\gamma - \vec{q}}{2} \right) \quad p' = q - q_\gamma + p = \left(\sqrt{M^2 + \frac{1}{4} (\vec{q}_\gamma - \vec{q})^2}, -\frac{\vec{q}_\gamma - \vec{q}}{2} \right)$$

- equally shared by initial and final nucleons
- similar to the sum over all momenta for Coh π^0 photoproduction
Carrasco et al., NPA565 (1993)

Coherent NC γ

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$
- Non-local treatment of Δ propagation
 - Factor $1/2$ correction according to the plane wave Coh π calculation of Leitner et al., PRC 79 (2009)
- However, this does not prove that local descriptions are a factor 2 off
- In order to (dis)prove this claim:
 - Take a realistic model with nonlocalities and non-local Δ spreading potential (Σ_{spr}) Nakamura et al, PRC 81 (2010)
 - Fit Σ_{spr} parameters to πA scattering with the same model
 - Take the local limit
 - Refit Σ_{spr} parameters to πA scattering
 - Compare results
- Our local approach already describes πA scattering, and Coh π^o photoproduction.

Coherent NC γ

- $\nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A$
- Non-local treatment of Δ propagation
 - Factor $1/2$ correction according to the plane wave Coh π calculation of Leitner et al., PRC 79 (2009)
 - The size of the correction is vertex dependent
 - In Coh π

$$J_\pi^\beta \sim \bar{u}(p_\pi)_\alpha \Lambda^{\alpha\beta} u$$

- In NC γ

$$J_\gamma^\beta \sim \bar{u} \epsilon^\mu (g_{\mu\alpha} \not{q}_\gamma - (q_\gamma)_\mu \gamma_\alpha) \Lambda^{\alpha\beta} \gamma_5 u$$

- Our local approach already describes πA scattering, and Coh π^o photoproduction.